WESTERN CURRENCY FACILITY

PRELIMINARY ASSESSMENT

July 2002

BUREAU OF ENGRAVING & PRINTING

Western Currency Facility

Fort Worth Texas

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ABBREVIATIONS AND ACRONYMS

BEP	Bureau of Engraving and Printing
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
EPA	Environmental Protection Agency
PA	Preliminary Assessment
WCF	Western Currency Facility

PRELIMINARY ASSESSMENT
BUREAU OF ENGRAVING AND PRINTING
WESTERN CURRENCY FACILITY

1.0 INTRODUCTION

A Preliminary Assessment (PA) was performed by the Bureau of Engraving and Printing (BEP), Western Currency Facility, located at 9000 Blue Mound Road, Fort Worth, Texas, Tarrant County. It was determined by the U.S. Environmental Protection Agency (EPA) that this assessment is required under the reporting mechanism RCRA Section 3010. Additionally, in accordance with Section 120(d) of the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), the EPA has determined that information necessary to assess the threat to human health and the environment must be provided to the EPA. This PA was completed by BEP personnel in July 2002. The purpose of this PA is to provide EPA with information to assess the disposition of the site in reference to CERCLA.

Prior to this assessment, an Environmental Assessment (EA) conforming to required NEPA documentation was completed in March 1987 before construction of the facility. The 1987 EA resulted in a Finding of No Significant Impact for the Western Currency Facility (Reference 7). Additionally, an Environmental Assessment was performed in February 2001 for an expansion to the facility (Reference 1).

2.0 SITE LOCATION, DESCRIPTION, OPERATIONAL HISTORY AND WASTE CHARACTERISTICS

2.1 Site Location

The U.S. Department of the Treasury, Bureau of Engraving and Printing has two facilities that print the entire supply of currency for the United States. One facility is located in Washington, D.C, and the other facility, the Western Currency Facility, is located in Fort Worth, Texas. The Western Currency Facility is located approximately one mile south of the intersection of FM Road 156 (Blue Mound Road) and U.S. 287/81 in far north Fort Worth, Texas. Prior to construction of the Western Currency Facility, the land was undeveloped and used for agriculture (pasture and field crops). Blue Mound Road is designated as a P6D (principal arterial, six lanes, divided) in the City's Master Thoroughfare Plan, but currently exists as a two-lane country road bounding the project site. U.S. 287 is a major four lane, divided thoroughfare in this area. It intersects with Interstate Highway 35W approximately 1.5 miles southeast of the facility. Approximately 800 feet south of the subject property, Harmon Road intersects Blue Mound from the east. Almost one mile east, Harmon turns directly north and intersects U.S. 287. The Bureau views Harmon Road as an alternate access route to its' facility (Reference 7).

2.2 Site Description

The U.S. Department of Agriculture, Soil Conservation Service, describes the soils of this site as having low fertility not suitable for cultivated crops, poor pasture or grazing potential, severe recreational use limitations, poor potential regarding wildlife habitat, and unsuitable for use as construction material or for water management projects. Terrain of the site is gently rolling plain. Local relief on the tract is about 36 feet (683 feet to 719 feet elevation) with the steepest slopes and lowest elevation toward the southwest corner. Natural drainage is to the Big Fossil Creek watershed. None of the subject property is within the designated 100-year floodplain. East of the proposed site, fronting on U.S. 287, are tracts of land, which are zoned for industrial use, with several now containing active operations. The dominant land use trend of this area appears to be toward commercial and industrial areas. A short section of Blue Mound Road north of the Western Currency Facility as well as the intersection of Blue Mound-Harmon are within the 100-year flood zone. However, planned future improvements along both Blue Mound and Harmon Road should eliminate any likelihood of closure due to flooding (Reference 7). The Western Currency Facility occupies a 100-acre tract of land in this area.

2.3 Operational History and Waste Characteristics

The Western Currency Facility of the Bureau of Engraving and Printing located at 9000 Blue Mound Road, Fort Worth, Texas manufactures U.S. banknotes and has been in operation since construction was completed in 1991.

Both sides of the notes are printed with an Intaglio printing process in 32 note sheets. These sheets are examined in the mechanical exam area and are then sent to the COPE-PAK area for overprinting and packaging. The printed currency is stored in a vault until shipped to Federal Reserve Banks. Printing currency is the main process at the plant and generates a large majority of hazardous and non-hazardous waste, including waste solvents. The facility is a large quantity generator and does not treat, store or dispose of hazardous waste on-site.

The printing plates used on the Intaglio presses are also manufactured in the plant. Plate manufacturing is a source of hazardous waste. The plates are manufactured with an electro-forming process using a nickel sulfonate bath and nickel anodes. The nickel plates are hardened by applying a 0.025 mm thick coating of chrome. This process generates several of the plant's hazardous waste streams. Typical hazardous wastes generated from the plate making process include waste chromic acid solution and waste liquid from the de-chroming process. Press rollers are also reconditioned in the plant. These rollers are coated with polyvinyl chloride, heat cured, and trimmed to the correct size and finish.

Construction of an ink reconstitution and manufacturing facility was completed in 1996 and began operation in 1997. This facility manufactures non-magnetic

Intaglio ink used in the plant to print higher denomination currency. Ink recovered from the Intaglio printing process is reconstituted for reuse in the plant (Reference 13).

3.0 GROUNDWATER MIGRATION PATHWAY

3.1 Hydrogeologic Setting

The most important water-bearing formation located beneath the Western Currency Facility is the Paluxy Formation. The Paluxy yields small to moderate amounts of fresh to slightly saline water to public supply, industrial, domestic and livestock wells to several nearby counties. The majority of the Paluxy outcrop occurs in Hood, Parker, Tarrant, and Wise Counties as illustrated in Figure 16 (Texas Department of Water Resources Report 269, Reference 4) and occupies about 650 square miles.

The primary source of recharge to the Paluxy is precipitation on the outcrop. Secondary sources include recharge from streams flowing across the outcrop and surface-water seepage from lakes. The Brazos and Trinity River systems and Eagle Mountain Reservoir are a few examples. The average annual precipitation on the outcrop is about 31 inches. Only a small fraction of the amount is available as effective recharge since there is much runoff and evapotranspiration.

Water in the outcrop area is under water-table conditions and water levels remain fairly constant with only normal seasonal fluctuations. In downdip areas, water is under artesian conditions, and is confined under hydrostatic pressure from overlying formations. The average rate of movement of water in the Paluxy amounts to less than 2 feet per year in an easterly direction except in downdip areas of heavy pumpage where cones of depression have occurred and movement is towards the center of the pumped wells. Water-level measurements indicate that the present hydraulic gradient is approximately 27 feet per mile. Altitudes of water levels in 1955 and 1976 are shown on Figures 30 and 31 (Texas Department of Water Resources Report 269, Reference 4).

Discharge from the Paluxy occurs naturally through springs and evapotranspiration and artificially through pumpage from water wells. In 1976, approximately 13,550 acre-feet was pumped from the Paluxy for municipal, industrial, irrigation, and domestic purposes. Livestock use would probably add several thousand acre-feet to this quantity.

Table 4 of Texas Department of Water Resources Report 269, Volume I shows the results of test wells in the Paluxy. Changes in water levels of wells completed in the Paluxy aquifer are illustrated by hydrographs (Figures 7 and 9) and a water-level decline map (Figure 32) showing approximate declines in the vicinity of Dallas and Tarrant Counties from around 1955 through 1976. There are no long-range declines in the outcrop of the Paluxy or adjacent to it. The aquifer is under water-table conditions in this region and observation wells show minor fluctuations from year to year (Reference 4).

Public supply wells pumped 8,320 acre-feet of ground water from the Paluxy in 1976. Development of the Paluxy, especially in Tarrant County, began at the turn of the century and by the 1950's, large quantities of water were being withdrawn. Industrial use accounted for 1,365 acre-feet in 1976, with only minor amounts of water for irrigation purposes being pumped from the Paluxy.

Wells completed in the Paluxy have water with chemical quality that is generally better than water from other Cretaceous aquifers. Most of the minor deficiencies found in the Paluxy water exist on or near the outcrop where hardness and higher iron concentrations occur.

Figure 20 shows the net sand thickness of fresh to slightly saline water-bearing sand in the Paluxy (Reference 4).

Subsurface conditions of the site underlying the Western Currency Facility were evaluated in 1987 prior to construction of the facility. Specimens of soil borings revealed variations in depth of underlying limestones. Brown to dark brown clays were encountered at the ground surface in most of the boring locations. These clays contained some pebbles and occasional limestone gravel and were slightly silty. The clays extended to depths, which varied from one (1) to four (4) feet in the various boring locations. The brown clays were underlain by tan silty and limey clays. These clays contained varying amounts of pebbles, inclusions, limestone gravel, sandy lenses and weathered limestone layers. Layers of fractured white limestone were encountered in these tan clays at varying depths and in varying frequency. Materials consisting primarily of the tan silty, limey clays extended to depths, which generally varied between five (5) and ten (10) feet.

White limestones were encountered below these clays at depths, which varied as indicated above. These white limestones were generally encountered as layers separated by layers of highly weathered shale and tan limey, silty clays. Some layers of white limestone were relatively hard being separated by very weathered shales and limestones and limey clays.

Transition to the unweathered blue limestones occurred at a depth of approximately ten (10) feet; however, variations in depth of eight (8) to fifteen (15) feet were encountered in the borings. The blue limestones were quite hard, but were interbedded with lenses and layers of relatively soft dark blue shale. The thickness of these shale layers was typically several inches but in some areas, thicknesses of six (6) to twelve (12) inches were encountered. Borings, which were made in the proposed structure area, were extended approximately fifteen (15) feet into the blue limestone and shale.

Atterberg limits tests indicated that the surficial brown to dark brown clays and silty clays encountered at the site are active. These soils are subject to potential volume changes (expansion or contraction) with fluctuations in their moisture content. The underlying tan silty to limey clays are not considered highly active; however, some layers of more plastic clay could be encountered in these materials. These limey clays could also be subject to some volume change, particularly if they are excavated and recompacted in a dry dense condition.

Static water level measurements made during a twenty-four (24) hour period after completion of the borings indicated water levels at depths of several feet to below twenty (20) feet. Water level measurements made six (6) days after drilling indicated static water levels at depths of approximately two (2) feet from the ground surface. Groundwater conditions encountered over the site are considered to be seasonal. Seepage can occur at various depths above the unweathered limestones. Groundwater conditions will also vary with seasonal rainfall (Reference 3).

3.2 Ground Water Targets

Currently, local ground water is not affected by wells, pumping or other aquifer penetrations. The Western Currency Facility operations do not obtain water from groundwater wells and the operations have no significant effect on groundwater (Reference 1).

3.3 Ground Water Conclusions

Existing groundwater aquifers have the potential of receiving rainfall runoff through percolation, however, because the Western Currency Facility has internal spill and overfill controls; illicit discharges to groundwater are unlikely. Because of this, no significant impact to groundwater exists (Reference 1).

4.0 SURFACE WATER MIGRATION PATHWAY

4.1 Hydrologic Setting

The site is located very close (less than 0.1 mile) to an upstream branch of Big Fossil Creek (Reference 5). The water migration path will be just following the creek's flow path. Major streams within 15 miles of the site include the following:

(a) Denton Creek
(b) Trinity River

(c) Bear Creek
(d) Clear Fork Trinity River

Major lakes within 15 miles of the site include:

(a) Eagle Mountain Lake
(b) Grapevine Lake
(c) Lake Worth
(d) Lake Arlington

4.2 Surface Water Targets

There are no direct discharges to natural surface waters. All wastewaters are pretreated and discharged to the City of Fort Worth sewers for further treatment at their publicly owned wastewater treatment facility in accordance with the Clean Water Act (Reference 1).

4.3 Surface Water Conclusions

Due to the fact that there are no direct discharges to natural surface waters, no significant impact to surface waters is observed (Reference 1).

5.0 SOIL EXPOSURE AND AIR MIGRATION PATHWAYS

5.1 Physical Conditions of the Soil

A recent subsurface investigation was conducted for an expansion to the existing facility. From results of the investigation conducted at the site, it was observed that overburden soils consist of tan, brown, light brown, dark brown, and dark gray silty sand, silty clay, shaly clay, and clay of low to high plasticity. The clayey soils are generally very stiff (soil basis) with pocket penetrometer readings ranging from 3.0 to 4.5 tsf. Liquid limits and plasticity indices of tested samples varied from 33 to 68, and 18 to 45, respectively. Unit weight and unconfined compressive strength values varied from 97 to 117 pcf, and 5300 and 26,700 psf, respectively (Reference 3).

The overburden soils are underlain by moderately hard to very hard tan limestone. The tan limestone was encountered at depths of 1 to 12 feet in the borings. THD cone penetrometer values in the tan limestone ranged from 0.0 to 6.5 inches of penetration per 100 blows. Gray shaly limestone underlies the tan limestone at a depth of 8 to 19 feet below ground. The gray shaly limestone is generally hard to very hard. THD cone penetrometer values varied from 0.0 to 2.75 inches of penetration per 100 blows. A more detailed description of native soils and their characteristics is attached (Reference 3).

5.2 Soil and Air Targets

The Western Currency Facility employs approximately 660 personnel on site. The Western Currency Facility is not operating on or near any sites eligible for nomination to the National Register of Historic Places or for designation as State Archeological Landmarks. Additionally, a response from the U.S. Fish and Wildlife Service indicated that wetlands would not be significantly impacted (Reference 1).

The surrounding property is zoned Business Park (IP). The land use is expected to remain as it presently exists. Currently no residential areas or schools, or day care facilities are located within 200 feet of the Western Currency Facility site. The Western Currency Facility is located in an area that is a mix of rangeland, farms, and industry. The general area is zoned Community Facilities (CF) and Industrial Park (IP). The nearest residential area and school is approximately one mile south of the WCF (Reference 1).

5.3 Soil Exposure and Air Migration Pathway Conclusions

The soil exposure pathway poses a minimal threat because all operations are performed inside the plant. No operations that could pose a threat to soil pathways, such as, activities involving hazardous materials, are performed outside, thereby negating the possibility of a release to the soil.

The worst-case scenario in regard to Air Migration Pathways lies in the possible release of sulfuric acid to the atmosphere during an accident or other spill event in the Waste Treatment section of the plant. Because internal controls exist to minimize the threat of such an event, this scenario is considered unlikely to occur (Reference 1).

An expansion to the Western Currency Facility is currently under construction. During construction of the expansion emissions primarily from construction equipment and vehicle internal combustion engine exhausts will be generated. These emissions and other waste products will be typical of any industrial construction site and are not considered significant.

6.0 Summary and Conclusions

Because of minimal or insignificant threats to groundwater, surface water, soil, and air, operations conducted at the Western Currency Facility pose little or no environmental impact to the surrounding area (Reference 1).

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2. Texas Water Well Development Board Groundwater Well Database.

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10. Population data for target communities.

11. Facility records regarding Air Emissions Monitoring.

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13. Bureau of Engraving and Printing 2000 Waste Minimization Plan.

TEXAS DEPARTMENT OF WATER RESOURCES

REPORT 269

OCCURRENCE, AVAILABILITY, AND CHEMICAL QUALITY OF GROUND WATER IN THE CRETACEOUS AQUIFERS OF NORTH-CENTRAL TEXAS

VOLUME 1

By

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OCCURRENCE, AVAILABILITY, AND CHEMICAL QUALITY OF GROUND WATER IN THE CRETACEOUS AQUIFERS OF NORTH-CENTRAL TEXAS

SUMMARY AND CONCLUSIONS

The study area consists of approximately 15,500 square miles (40,145 km^2) and lies within the Red, Sulphur, Sabine, Trinity, and Brazos River basins. The region includes all or parts of Collin, Cooke, Dallas, Delta, Denton, Ellis, Fannin, Grayson, Hood, Hunt, Johnson, Kaufman, Lamar, Montague, Navarro, Parker, Red River, Rockwall, Tarrant and Wise Counties.

The Trinity Group of Cretaceous age is the largest and most prolific aquifer in the study area. The aquifer consists of the Antlers, Paluxy, and Twin Mountains Formations. The Antlers is a coalescence of the Paluxy and Twin Mountains in the northern part of the study area where the Glen Rose Limestone is absent. The Trinity Group aquifer ranges in thickness from about 100 feet (30 m) in the outcrop area to about 1,200 feet (366 m) near the downdip limit of fresh to slightly saline water. The transmissibility is highly variable with average values ranging from 3,700 (gal/d)/ft or 45,900 (l/d)/m in the Paluxy and in the Antlers near Sherman to over 10,000 (gal/d)/ft or 124,000 (l/d)/m in most downdip areas of the Twin Mountains and in the Antlers near Gainesville. A wide range in permeabilities is also encountered, but an overall value of 50 (gal/d)ft^2 or 2,040 (l/d)/m^2 is average. Artesian storage coefficients range from 0.0001 to 0.00025 and specific yields range from 15 to 25 percent in the outcrop.

Chemical quality in the Trinity Group aquifer updip from the fresh to slightly saline water limit is suitable for most public supply and industrial uses. Irrigation is usually limited to the outcrop area and quality is fair for most crops. Generally, water from wells on or near the outcrop is harder than ground water downdip and it also contains high iron concentrations in some areas. The Twin Mountains Formation contains high dissolved solids in an area centered in southeastern Wise County and is generally of poor quality along the Parker and Tarrant Counties boundary line.

Yields of wells completed in the Trinity Group aquifer increase in a downdip direction with wells producing up to 1,900 gal/min (120 l/s). Yields of wells completed on or near the outcrop are low, with maximum yields of 50 gal/min (3.2 l/s) not uncommon. Wells in the Antlers and Twin Mountains Formations have much higher yield averages than wells producing from the Paluxy Formation. However, the areal extent of groundwater production is larger in the Paluxy than in the Antlers and Twin Mountains. Paluxy wells have been developed in 16 of the 20 counties as compared to only 14 counties for the Antlers and Twin Mountains.

Water-level declines have been recorded in the Trinity Group since water-level records began in the first part of the 20th century. Significant cones of depression have formed in the Antlers around Gainesville and Sherman. The large cone of depression in the Dallas-Fort Worth metroplex involves both the Paluxy and Twin Mountains. Static water levels in this area have reached the top of the Paluxy and dewatering of the aquifer has begun, while static water levels in the Twin Mountains have reached 1,000 feet (305 m) below the land surface. Declines of over 20 feet (6 m) per year is not uncommon in the area along the Dallas and Tarrant counties boundary line. The abandonment of many Trinity wells in this area has alleviated the problem somewhat, but the large quantity of ground water pumped from surrounding areas will cause a continuation of the trend in water-level declines. Diminishing yields, lowering of pumps, and high lifting costs will continue to plague ground-water users. Water levels outside the influence of heavily pumped areas are also experiencing declines, but at a slower rate.

Total pumpage for public supply, industrial, and irrigation purposes from the Antlers, Twin Mountains, and Paluxy Formations in 1976 was, respectively 8,870 acre-feet (10.9 hm^3), 38,600 acre-feet (47.5 hm^3), and 10,000 acre-feet (12.3 hm^3). With the additional pumpage of ground water for domestic and livestock purposes, the Trinity Group aquifer yielded over 66,000 acre-feet (81.4 hm^3) of water to wells in the study area. The total average annual ground-water availability for the Trinity Group in the study area to the year 2030 is 63,000 acre-feet (77.7 hm^3) which includes an annual effective recharge of 51,000 acre-feet (62.9 hm^3). The large discrepancy in pumpage and effective recharge emphasizes the fact that the Trinity Group aquifer is overdeveloped. Further development of ground water at present pumpage rates will continue to lower the piezometric surface and deplete storage that cannot be replenished.

The Woodbine Group provides water for all purposes to approximately half of the counties covered in this study. The group is divided into three water-bearing parts-upper, middle, and lower-which vary considerably in productivity and quality. The upper Woodbine contains water of extremely poor quality in downdip locales and contains excessive iron concentrations along the outcrop. In general, water from this part is sealed off in all wells except those used for irrigation, where iron content is not important. The middle Woodbine generally contains water of good quality; however, high iron concentrations occur in some areas. Yields are moderate and water from this part is utilized in most wells. The lower Woodbine is the most productive and contains good quality water. High yields are characteristic in this part from the outcrop downdip to the slightly saline limit which is approximately 2,000 feet (610 m) below land surface.

Total thickness of the Woodbine ranges from 230 feet (70 m) near the outcrop to 700 feet (21 3 m) near the downdip limit of fresh to slightly saline water. The net sand thickness is less than 350 feet (10 7 m) with most of this occurring in the lower Woodbine. The average artesian coefficient of storage is 0.00015 where the Woodbine is under artesian conditions, and the specific yield is about 15 percent. Transmissibility values in downdip areas average 4,700 (gal/d)/ft or 58,400 (l/d)/m and permeability values average 44 (gal/d)/ft^2 or 1,790 (l/d)/m^2.

Chemical quality deteriorates rapidly in well depths below 1,500 feet (457 m). In areas between the outcrop and this depth, quality is considered very good overall as long as ground water from the upper Woodbine is sealed off. Water is classified as soft with most chemical analyses showing total hardness as calcium carbonate below 60 mg/l.

Yields of wells completed in the Woodbine averaged 160 gal/min (10 l/s) with measured quantities of as much as 1,170 gal/min (74 l/s). The average specific capacity calculated from production tests was 2.9 (gal/min)/ft or 0.60 (l/s)/m. Wells operating under artesian conditions are experiencing declines in water levels. Declines of a few feet (less than a meter) per year to over 10 feet (3 m) per year have been recorded. Declines in the Sherman area (Grayson County) are steepest and are depicted as a cone of depression on water-level maps. The steady decline is a result of low permeabilities in water-bearing sands and large withdrawals by ground-water users.

Approximately 16,000 acre-feet (19.1 hm^3) of ground water was pumped from the Woodbine in 1976 from wells in the study region. Public supply pumpage accounted for 8,560 acre-feet (10.6 hm^3) in 1976, while industrial and irrigation users added over 2,500 acre-feet (3.08 hm^3) each to this quantity. The average annual ground-water availability as effective recharge is 24,500 acre-feet (30.2 hm^3) over the entire aquifer. This maximum quantity is based on uniform use along the entire aquifer after water levels have been lowered to a maximum of 400 feet (122 m) below the land surface. Water levels will continue to decline in heavily pumped areas. However, at the present withdrawal rate, when considered collectively, the aquifer is in no immediate danger of overdevelopment.

Information was collected on several minor water-bearing formations within the study region and all pertinent data have been included in this report. The minor aquifers included in the study are the Paleozoic rocks undifferentiated, Blossom Sand, Nacatoch Sand, and alluvium. The primary use of these aquifers is for domestic and livestock purposes although several municipalities pump from them. The Paleozoic rocks provide water mainly in Montague County with smaller usage in Wise, Parker, and Hood Counties. The Blossom and Nacatoch Sands of Cretaceous age provide ground water to wells along the eastern portion of the study area. Minor amounts of water are pumped from the alluvium along the Red River for irrigation and livestock needs.

Wells completed in the Nacatoch and Blossom Sands produce up to 500 gal/min (32 l/s) for public supply use in local areas. In regions of heavy pumpage such as around Clarksville in Red River County and Commerce in Hunt County, water levels are declining steadily. A total of 2,700 acre-feet (3.33 hm^3) of water was pumped from these aquifers in 1976 for public supply and industrial purposes. Domestic and livestock usage probably exceeds this amount. The estimated average annual amount of ground water available as effective recharge from both aquifers is about 1,620 acre-feet (2 hm^3). Annual water-level declines are a direct result of the deficit between pumpage and effective recharge.

INTRODUCTION

Purpose and Scope

The general purpose of this study was to determine the ground-water resources of the Cretaceous aquifers in north-central Texas, with emphasis on the Woodbine and Trinity Groups. Field investigations were conducted during the period from January 1975 to August 1978. Aquifers comprising the Trinity Group consist of the Antlers, Paluxy, and Twin Mountains Formations which are the most important water-bearing units in the study region. The study area is shown on Figure 1.

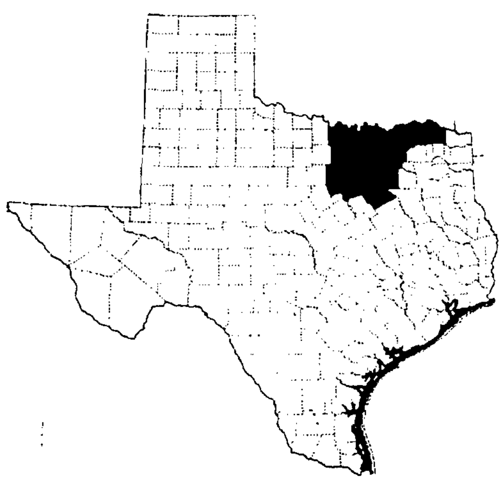


Figure 1.—Location of Study Area

The primary purpose of this study was to determine the occurrence, availability, quality, and quantity of ground water used for municipal, industrial, and irrigation purposes from the Woodbine and Trinity Groups of Cretaceous age. The secondary purpose was to include data on minor aquifers being utilized within the study region such as the Paleozoic rocks undifferentiated, Blossom Sand, Nacatoch Sand, and alluvium.

The general scope of this investigation included the collection, compilation, and analysis of data relating to ground water from the Cretaceous aquifers in north-central Texas, and the presentation of these data, results of analyses, and conclusions in a published report. The report consists of two volumes. Volume 1 contains interpretive information presented as text and related figures and tables. Volume 2 contains supporting basic data including well location maps, records of wells, water-level measurements, and chemical analyses of water.

The scope, although directed toward the quantitative aspects of water availability, also included collection and use of chemical-quality data, surface and subsurface geological data, study of ground-water contamination by oil and gas field operations in the west and northwest part of the study area, and review of previous work by federal and state agencies.

Location and Extent

The study region has an areal extent of 15,500 square miles (40,145 km^2) and represents 5.8 percent of the State's total area. It is bounded on the north by the Red River, on the west by the physical limit of the Cretaceous rocks, and on the east by the downdip limit of fresh to slightly saline water. For the purpose of this report, usable ground water is considered to be water that contains less than 3,000 milligrams per liter (mg/l) dissolved solids. The region includes all or parts of Collin, Cooke, Dallas, Delta, Denton, Ellis, Fannin, Grayson, Hood, Hunt, Johnson, Kaufman, Lamar, Montague, Navarro, Parker, Red River, Rockwall, Tarrant, and Wise Counties and lies within the Red, Sulphur, Sabine, Trinity, and Brazos River basins.

Physiography

The portion of Texas defined by the boundaries of the study area has been divided into a number of distinct physiographic subdivisions, which are also coincidental with the geologic units. The topography of a dissected region is determined chiefly by the nature of the underlying parent rock. According to Fenneman (1938) and Fenneman and Johnson (1946), the study area can be divided into six north-south trending belts which are clearly marked by distinctive soil, plant, and topographic characteristics. These belts, from west to east, are: the Osage Plains, the Western Cross Timbers, the Grand Prairie, the Eastern Cross Timbers, the Black Prairie, and the East Texas Timber Belt.

The Osage Plains is underlain by rocks of Paleozoic age and forms the western boundary of the study region. Its contact with the Western Cross Timbers coincides with the outcrop of Cretaceous rocks.

The Western Cross Timbers is underlain by the Trinity Group and also, in the south western part of the study area, by the Walnut Formation. This belt is characterized by a rolling to hilly topography that is dissected into steep hills and deep ravines. The very sandy soil supports a heavy growth of post oak and blackjack oak.

The Grand Prairie is underlain by alternating limestones and marls of the Washita and Fredericksburg Groups. The intervening marls form low escarpments that connect successive uplands and produce a "cuesta" topography. The surfaces of the terraces slope gently eastward, broken only by the westward-facing escarpments. The thin mantle of light brown to black loamy soil is well drained and its characteristics differ depending on the nature of the underlying material. The broad, gently rolling, grass-covered plain is usually *treeless except for isolated clumps of upland timber.*

The Eastern Cross Timbers coincides with the narrow belt of the Woodbine Group outcrop and is characterized by low, rounded, wooded hills along the western margin and gentle slopes along the eastern margin. It is well d ssected by streams leaving some areas quite rugged in appearance. The soil is reddish sand with iron concretions and some clay. The surface supports a dense growth of timber, consisting chiefly of post oak and blackjack oak.

The remaining Cretaceous formations and the Midway Group form the base of the Black Prairie. It is characterized by a relatively flat to gently undulating surface that slopes gently to the east. The Black Prairie is poorly drained constituting the famous blackland soil and relatively treeless.

A *small part of the study region falls* within the East Texas Timber Belt which is underlain by the Wilcox and has a sandy, slightly hummocky surface.

Land-surface elevations range from 1,450 feet (442 m) in the west to 250 feet (76 m) above mean sea level in the northeast. The 20-county area lies within the Red, Sulphur, Sabine, Trinity, and Brazos River basins. Drainage is to the southeast.

Climate

The climate of the region covered by this report is characterized by long, hot summers and short, mild winters. The average minimum temperature for January, the coldest month, ranges from 32°F (0°C) in the northwest to 36°F (2°C) in the southeast. The average maximum temperature for July, the hottest month, is 96°F (36°C) throughout most of the study area. The annual mean free air temperature for the period 1931-70 averaged 65" F (18°C).

The average annual precipitation ranges from 30 inches (76 cm) in the northwest to 45 inches (114 cm) in the northeast. These figures are based on National Weather Service records for the 77-year period 1900-76, and are illustrated on Figure 2 along with average monthly precipitation for periods of record at selected stations.

The average annual gross lake surface evaporation for the period 1940-70 ranges from 78 inches (198 cm) in the north-central area to 61 inches (155 cm) in the southeast.

Population

According to the 1978-79 Texas Almanac, the estimated 1975 populatior for the study region is over 2.75 million people, which is an average of 180 people per square mile (69.5 per km^2). This represented about 25 percent of the State's population. More than 85 percent of the people in this region lived in urban areas having 2,500 or more inhabitants. Some of the urban areas are Bonham, Clarksville, Cleburne, the Dallas-Fort Worth metroplex, Decatur, Denton, Gainesville, Granbury, Greenville, Lewisville, McKinney, Paris, Plano, Sherman, Waxahachie, and Weatherford. The remaining inhabitants lived in rural areas or smaller communities.

Economy

The *general economy is varied. Principal* manufacturing plants are in or near large cities; however, some plants in smaller cities process local products. Manufacturing, transportation, business, and insurance are of primary importance in the Dallas-Fort Worth area. About one-third of the counties in the study region produce petroleum products. Cooke and Montague Counties have produced about 475 million barrels of oil since the mid-1920's. Agricultural economy, which averages about 230 million dollars per year, consists of cattle and poultry raising and dairy products with grain, grain sorghums, peanuts, cotton, and soybeans the principal crops. Industrial activities include the operation of sand and gravel pits, the production of clay and manufacture of brick and tile products, the production of cement materials, and the manufacture of cement.

Previous Investigations

Portions of the study region have been previously discussed in numerous publications related to geology

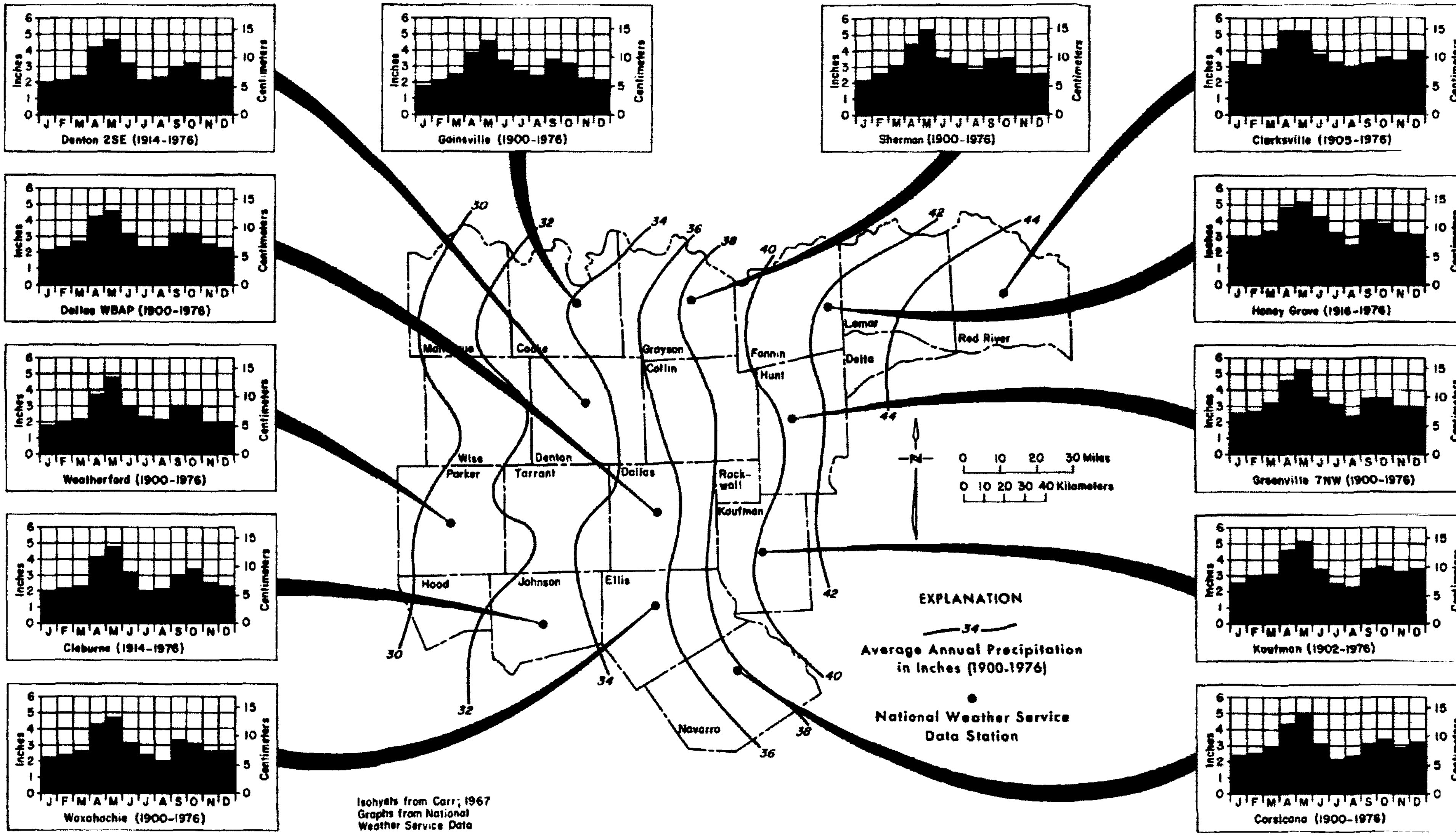


Figure 2

Average Annual Precipitation, 1900-1976, and Average Monthly Precipitation for Period of Record at Selected Stations and ground-water resources, and these are listed in the selected references. Some of the investigations leading to these publications were conducted by the U.S. Geological Survey, Texas Department of Water Resources, Bureau of Economic Geology of the University of Texas, private concerns, and educational institutes.

Reports have been published on the geology of Cooke, Denton, Grayson, Johnson, and Parker Counties and on the ground-water resources of Dallas, Ellis, Grayson, Johnson, Montague, Navarro, Parker, and Tarrant Counties. Most of these publications were published prior to 1960.

Acknowledgements

Recognition is extended to the property owners within the study region for supplying information concerning their water wells and permitting access to their properties; and to all water well drillers, city officials, water superintendents, and officials of independent water companies for information, assista-ce, and cooperation rendered throughout the investigation. Cooperation of federal and other state agencies is also gratefully acknowledged. Special thanks are extended to J. L. Myers Co., Layne Texas Co., and Henry Millican for the extensive use of their water-well records and electric logs.

The author also thanks Dan Muller and Bob Price of the Texas Department of Water Resources who made many useful suggestions concerning the ground-water availability estimates and to Loyd Walker for his review and editing of the manuscript. General supervision in the preparation of this report was furnished by C. R. Baskin, Director, Data and Engineering Services Division, and Tommy R. Knowles, Chief of the Data Collection and Evalution Section.

Method of Investigation

The fieldwork for this investigation began in January 1975 and ended in April 1978. Office work, which consisted mainly of assembling data and writing the report, started concurrently with the fieldwork and was completed in August 1978.

Fieldwork consisted of conducting a complete inventory of municipal, industrial, and irrigation water wells; conducting an inventory of historical pumpage; collect ng past and present water levels; collecting data on well construction, yields, pumping rates, and pumping levels; collecting drillers' logs, mechanical logs, and well completion data; determining elevations of wells having water level or stratigraphic data; conducting power and yield tests on selected irrigation wells; mapping surface geology; determining the chemical quality of ground water by using available analyses and collecting water samples for analysis, where needed; and determining the magnitude and extent of ground-water contamination in the outcrop area. Office work included constructing geologic cross-sections; tabulating water-well records, water levels, and chemical analyses; preparing well-location maps; constructing geologic maps of net sand thickness, structure, piezometric surface, chemical quality, surface geology, transmissibility, and water-level decline; and tabulating historical pumpage and projecting future water demands based on population, economic growth, and precipitation.

Well-Numbering System

The systematic well numbering used in this report was originally developed by the Texas Water Commission and is now in use statewide. It was designed to identify, facilitate the location of, and avoid duplication of numbers on all wells used in any Department report, investigation or study. The system is based on division of the State into one-degree quadrangles of latitude and longitude and the repeated division of these quadrangles into smaller ones as shown in Figure 3.

Each one-degree quadrangle is subdivided into sixty-four 7 1/2-minute quadrangles, and these quadrangles are further subdivided into nine 2 1/2-minute quadrangles. Each one-degree quadrangle has an assigned number. The 7 1/2-minute quadrangles are numbered consecutively from left to right, beginning with quadrangle number 01 in the upper left-hand corner of the one-degree quadrangle. The 2 1/2-minute quadrangles within each 7 1/2 minute quadrangle are numbered similarly. The wells are numbered consecutively, beginning with 01, within each 2%minute quadrangle. From left to right, the first and second digits of a well number identify the one-degree quadrangle in which the well belongs; the third and fourth digits, the 7 1/2-minute quadrangle; and the fifth digit, the 2 1/2-minute quadrangle. The sixth and seventh digits identify the particular well in the 2 1/2-minute quadrangle.

On the well location maps in this report, the one-degree quadrangles are identified with large open-block numbers. The 7 1/2-minute quadrangles are numbered in the upper left-hand corner or as near to that position as possible in the cases where a part of the quadrangle falls outside the county. The three-digit numbers near the wells identify the 2 1/2-minute quadrangle and the well within that quadrangle.

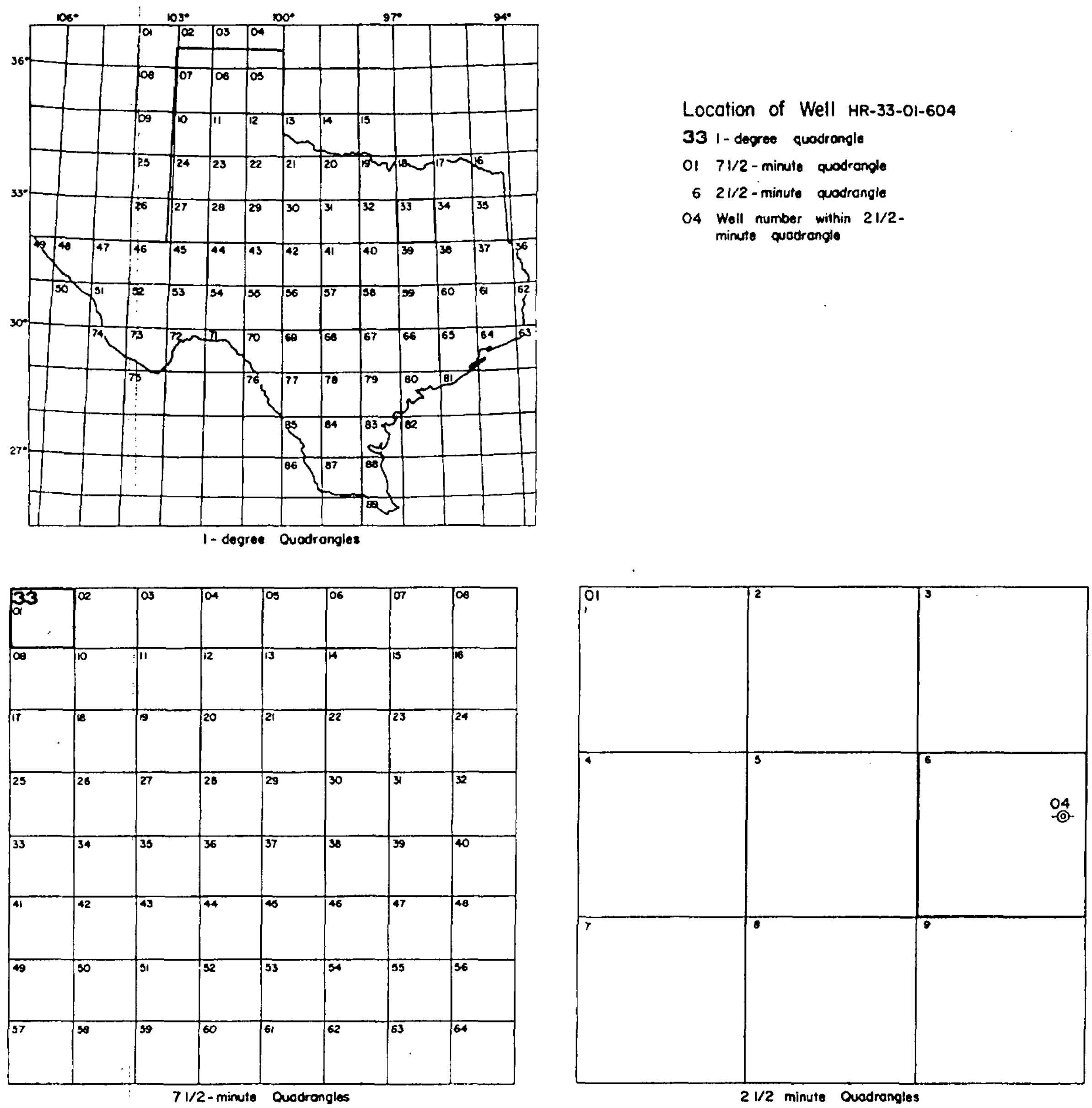


Figure 3.—Well-Numbering System

In addition to the seven-digit well number, a two letter prefix is used to identify the county. The prefixes for the 20 counties in this report are:

Prefix	County	Prefix	County
DT	Collin	KT	Grayson
HA	Cooke	LY	Hood
HR	Dallas	PH	Hunt
HU	Delta	PX	Johnson
HW	Denton	RA	Kaufman
JK	Ellis	RT	Lamar
JS	Fannin	TR	Montague
TY	Navarro	WL	Rockwall
UP	Parker	XU	Tarrant
WB	Red River	ZR	Wise

Well HR-33-01-604, shown on Figure 3, is in Dallas County (HR); 1-degree quadrangle 33; 7½-minute quadrangle 01; 2½-minute quadrangle 6; and was the fourth well inventoried in that 2½-minute quadrangle.

METRIC CONVERSIONS TABLE

For those readers interested in using the International System (SI) of Units, the metric equivalents of English Units of measurements are given in parentheses in the text. The English units used in this report may be converted to metric units by the following conversion factors:

Multiply English units	BY	To obtain SI units
acres	0.4047	square hectometers (hm^2)
acre-feet (acre-ft)	.001233	cubic hectometers (hm^3)
cubic feet per second (ft^3/s)	28.32	liters per second (l/s)
feet (ft)	.3048	meters (m)
feet per mile (ft/m)	.189	meters per kilometer (m/km)
gallons (gal)	3.785	liters (l)
gallons per minute (gal/min)	.06309	liters per second (l/s)
gallons per minute per foot [(gal/min)/ft]	.207	liters per second per meter [(l/s)/m]
gallons per day per square foot [(gal/d)/ft^2]	40.74	liters per day per square meter [(l/d)/m^2]
gallons per day per foot [(gal/d)/ft]	12.418	liters per day per meter [(l/d)/m]
inches (in)	2.54	centimeters (cm)
miles (mi)	1.609	kilometer (km)
square miles (mi^2)	2.590	square kilometers (km^2)

To convert degrees Fahrenheit (°F) to degrees Celsius (°C) use the following formula:

$$^{\circ}C = (^{\circ}F-32)(0.556)$$

GEOLOGY AS RELATED TO THE OCCURRENCE OF GROUND WATER

Geologic History

Paleozoic

During most of the Paleozoic era, a sedimentary basin existed throughout much of central and north-central Texas which received sediments consisting of sandstone, limestone, carbonaceous shales, and other marine sediments. Sediments were deposited in this basin until late Pennsylvanian time when the Llano Uplift and the Ouachita Fold Belt caused a regional tilting to the west and faulting in the immediate uplift area. The Pennsylvanian-Cretaceous unconformity shows a tremendous period of emergence and erosion. During Permian time, the basin shifted to the west and only the northwest corner of the study area received sediments, while the remainder of the area underwent extensive erosion.

Cretaceous

During the Triassic and Jurassic periods of the early Mesozoic era, withdrawal of the seas from the north-central Texas area along with subsidence in the Gulf Coast embayment led to a reversal of drainage direction. This resulted in an extensive truncation of Pennsylvanian strata in the Fort Worth basin and surrounding area. By the close of Jurassic time, Paleozoic rocks had been reduced to an almost flat-featureless plain, or peneplain, upon which marine sediments were deposited along an oscillating shoreline during the Cretaceous period.

Two major invasions of the seas during the Cretaceous period are represented by the Comanche and Gulf Series. During late Cretaceous (Gulf Series), a general uplift occurred to the west and the seas withdrew gullfward covering only the eastern portion of the study area.

Tertiary and Quaternary

At the close of the Cretaceous period, noted by uplifting of the western area and subsidence of the coastal area, sediments of Tertiary and Quaternary age were deposited. The repeated transgression and regression of the sea resulted in an alternating sequence of marine and continental deposits. Throughout Tertiary time, except for minor periods of subsidence, the land surface was eroded and modified by streams. During Quaternary time, the streams deposited alluvial sediments. The older sediments are represented by terrace deposits above the alluviated valleys of present streams.

General Stratigraphy

Stratigraphic units that supply fresh to slightly saline water to wells in the study region range in age from Paleozoic to Recent. The most important water-bearing formations in north-central Texas are of Cretaceous age.

The Cretaceous System is composed of two series, Gulf and Comanche, and each is divided into groups. The Gulf Series is divided into the following five groups: Navarro, Taylor, Austin, Eagle Ford, and Woodbine. The Comanche Series is divided into the following three groups: Washita, Fredericksburg, and Trinity.

The Taylor and Eagle Ford Groups consist predominantly of shale, limestone, clay, and marl and yield only small amounts of water in localized areas. The Navarro and Austin Groups consist of chalk, limestone, marl, clay, and sand and, except for the Nacatoch and Blossom Sands, yield only small amounts of water locally. The Nacatoch Sand of the Navarro Group and the Blossom Sand of the Austin Group yield small to moderate supplies of water to limited areas. The Woodbine Group is the only important aquifer of the Gulf Series in the area covered by this report. It consists of sand, sandstone, and clay and is capable of yielding small to large amounts of water. The Woodbine Group is discussed in detail in the sections covering the stratigraphy of the water-bearing formations and the occurrence and the availability of ground water.

Both the Washita and Fredericksburg Groups of the Comanche Series consist predominantly of limestone, shale, clay, and marl and yield only small amounts of water to localized areas. The Trinity Group is the principal water-bearing group of rocks in the region and is divided into the Paluxy, Glen Rose, Twin Mountains, and Antlers Formations. The Paluxy consists of sand and shale and is capable of yielding small to moderate amounts of water. The Glen Rose is predominantly a limestone and yields small quantities of water only to localized areas. The Twin Mountains is composed of conglomerate, sand, and shale. It is the principal water-bearing formation of Cretaceous age in the region and yields moderate to large amounts of water. The name Antlers Formation is applied north of the Glen Rose pinch-out, where the Paluxy and Twin Mountains coalesce to form one unit. Water-bearing members of the Trinity Group are discussed in detail in the sections covering stratigraphy of the water-bearing formations and occurrence and availability of ground water.

The relationship, approximate maximum thickness, brief description of lithology, and summary of water-bearing properties of the stratigraphic units are shown in Table 1. Outcrop areas of the various formations are illustrated on the geologic outcrop map (Figure 16). The altitude of the top of the formations and their net sand thicknesses are shown on Figures 18 through 22, 27, and 29.

Geologic cross-sections are profiles portraying an interpretation of a vertical section of the earth. Five geologic cross-sections were constructed; two are strike sections and three are dip sections. Dip sections are constructed approximately perpendicular to the strike of the beds and parallel to the dip of the beds, while strike sections are constructed parallel to the strike of the beds. These five geologic: sections, illustrated on Figures 35 through 39, show the structure and stratigraphic relationships of the geologic units.

Structure

Pennsylvanian and Permian rocks in the outcrop along the west edge of the study area dip westward and northwestward at about 40 feet per mile (7.6 m/km). Permian beds probably extend not much farther eastward than Montague County. The Pennsylvanian sediments, which underlie the Cretaceous rocks in most of the remaining area, thicken from the outcrop eastward into the Fort Worth basin. The axis of this basin and many of the other major structural features in or near the report area are shown on Figure 4.

The Cretaceous System forms a southeastward-thickening wedge extending across the area into a structural feature known as the East Texas basin. Thickness of these rocks ranges from zero in the west to nearly 7,500 feet (2,286 m) in the southeast. Regional dip is east and southeast at rates of about 15 to 40 feet per mile (2.8 to 7.6 m/km). The dip rate increases to as much as 300 feet per mile (57 m/km) on the southeastward-plunging ridge called the Preston anticline. This anticline and an associated trough to the south (Sherman syncline) have caused a change in the regional outcrop pattern as shown on the geologic map (Figure 16).

Tertiary System beds dip regionally southeastward from the Mexia-Talco fault system, which extends in a northerly direction along the eastern margin of the report area, at a rate of about 100 feet per mile (19 m/km). Deviations from this dip rate occur locally due to the faulting. These beds attain a thickness of approximately 250 feet (76 m) within the area of study. However, just outside the area of investigation in southern Navarro County they reach a maximum thickness in excess of 1,000 feet (305 m).

Quarternary deposits occur along the floodplains of the Brazos, Red, Sulphur, and Trinity Rivers and

Table 1.—Stratigraphic Units and Their Water-bearing Properties

Yield, in gallons per minute (gal/min): small, less than 100 gal/min; moderate, 100–1,000 gal/min; large, more than 1,000 gal/min.

Era	System	Series	Group	Stratigraphic units	Approximate maximum thickness (feet)	Character of rocks	Water-bearing characteristics
Cenozoic	Quaternary	Recent		Alluvium	75	Sand, silt, clay and gravel.	Yields small to large amounts of water to wells along the Red River
		Pleistocene		Fluviatile terrace deposits			
	Tertiary	Eocene	Wilcox		100	Fine to medium sand with silt and clay	Yields small quantities of water to wells in the eastern part of the area.
		Paleocene	Midway		150	Gray, calcareous clay, in part silty to sandy	Do.
Mesozoic	Cretaceous	Gulf	Navarro	Kemp Clay Corsicana Marl	300	Fossiliferous clay and hard limy marl	Not known to yield water to wells in the area.
				Nacatoch Sand	500	Fine sand and marl, fossiliferous	Yields small to moderate quantities of water near the outcrop.
			Taylor	Marlbrook Marl Pecan Gap Chalk Wolfe City - Ozan Formations	1,500	Clay, marl, mudstone, and chalk	Yields small quantities of water to shallow wells.
			Austin	Gober Chalk Brownstown Marl Blossom Sand Bonham Formation	700	Chalk, limestone, and marl; fine to medium sand, fossiliferous	Yields small to moderate quantities of water to wells in the northeastern part of the area; very limited as an aquifer.
			Eagle Ford		650	Shale with thin beds of sandstone and limestone	Yields small quantities of water to shallow wells.
			Woodbine		700	Medium to coarse iron sand, sandstone, clay and some lignite	Yields moderate to large quantities of water to municipal, industrial and irrigation wells.
		Comanche	Washita	Grayson Marl - Mainstreet Limestone Pawpaw Formation - Weno Limestone - Denton Clay Fort Worth - Duck Creek Kiamichi Formation	1,000	Fossiliferous limestone, marl, and clay; some sand near top	Yields small quantities of water to shallow wells.
			Fredericksburg	Edwards Limestone Comanche Peak Formation — Goodland Limestone Walnut Formation	250	Limestone, clay, marl, shale, and shell agglomerates	Do.
			Trinity	Antlers Formation: Paluxy Formation	900: 400	Fine sand, sandy shale, and shale	Yields small to moderate quantities of water to wells.
				Antlers Formation: Glen Rose Formation	900: 1,500	Limestone, marl, shale, and anhydrite	Yields small quantities of water in localized areas.
				Antlers Formation: Twin Mountains Formation	900: 1,000	Fine to coarse sand, shale, clay, and basal gravel and conglomerate	Yields moderate to large quantities of water to wells.
Paleozoic				Paleozoic rocks undifferentiated		Sandstone, limestone, shale and conglomerate	Yields small quantities of water in the western part of the area.

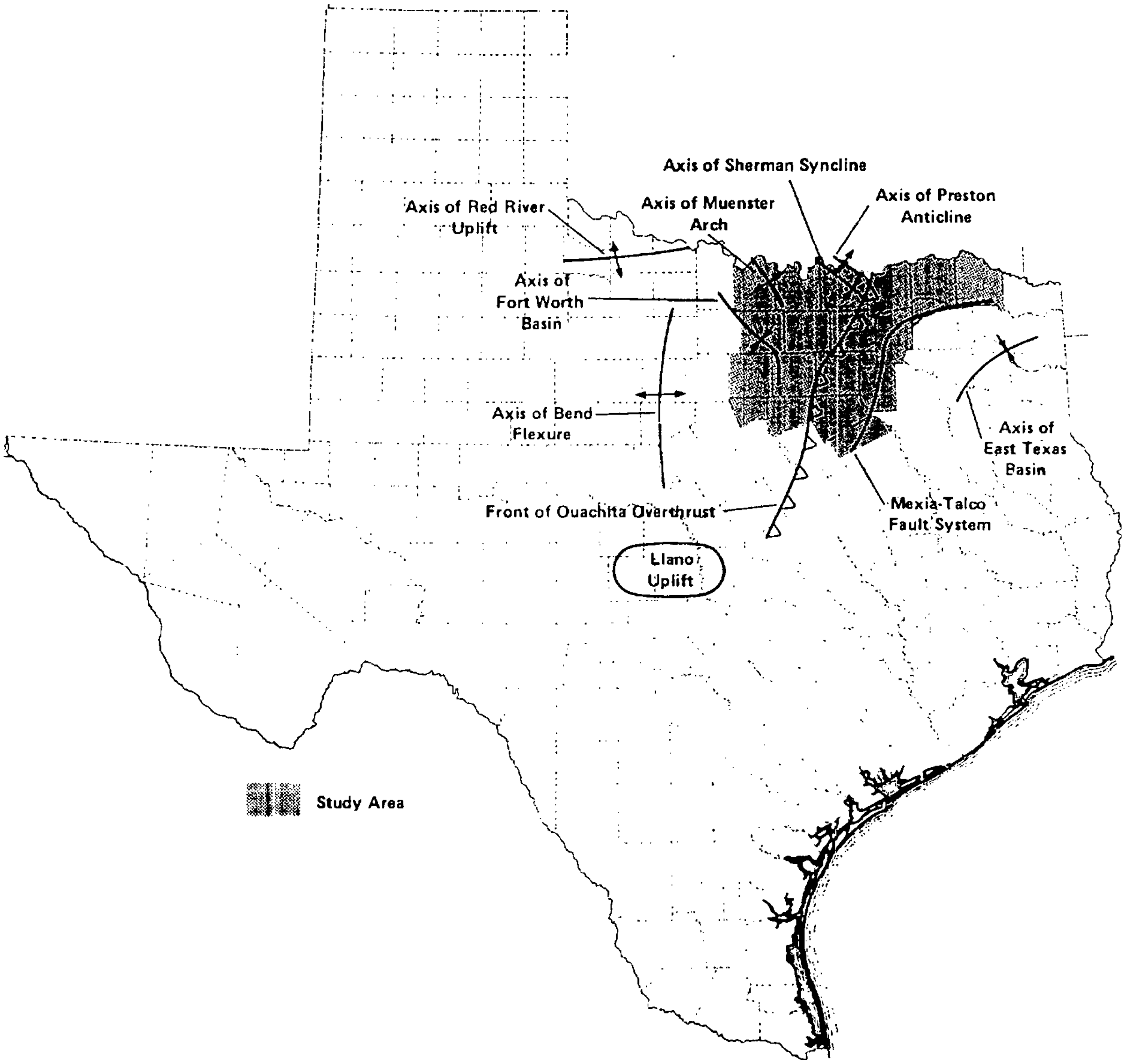


Figure 4.—Major Structural Features From the Llano Uplift to the Red River

many of their main tributaries. Terraces, which represent remnants of older floodplain deposits of these drainage systems, occur at higher elevations along some of the rivers, particularly the Red River. Alluvial deposits are reported to be as thick as 70 feet (21 m) in Fannin County. Generally, the alluvial deposits are irregular in thickness and areal extent. Regional slope of these deposits is probably less than 5 feet per mile (0.9 m/km) and generally east and southeast in the direction of slope of the land surface. Locally, the direction will vary according to the direction of stream or river flow.

STRATIGRAPHY OF THE WATER-BEARING FORMATIONS

Paleozoic Rocks

Paleozoic rocks crop out in the western part of the study area in Hood, Montague, Parker, and Wise Counties (Figure 16). The occurrence of ground water with acceptable quality in these rocks is generally limited to the outcrop and adjacent area. Figure 17 shows the approximate altitude of the base of

Cretaceous rocks, which is the top of the Paleozoic in the western part of the study area.

Of the many pre-Cretaceous rocks cropping out along the western edge of the study region, only the Wichita Group of the Permian System and several formations in the Cisco and Strawn Groups of the Pennsylvanian System yield water in any appreciable quantity and of good quality.

The Wichita Group crops out in the northwest third of Montague County and consists of fossiliferous limestone, shale, and sandstone. Sandstone is more abundant in the lower part of the group, however, the amount of sand diminishes downdip. For this reason, wells pumping ground water from this lower sandstone are located on or very near the outcrop. The rocks dip gently toward the west or northwest.

The Cisco Group crops out in the southwest corner of Montague County and underlies the Wichita Group to the north. The Cisco Group consists of alternating beds of shale, sandstone, limestone, and conglomerate. As in the Wichita Group, there is less sand downdip than in the outcrop. In the study area, rocks of Pennsylvanian age generally dip toward the west or northwsst at a rate of approximately 50 feet per mile (9.5 m/km) and are overlain by the Trinity Group of Cretaceous age to the east.

The Strawn Group crops out in the western portion of Parker County. The Garner Formation of the Strawn Group in the northern part of the outcrop is the only source of water for wells in this part of the study area. Ground water is derived from the Brazos River Conglomerate Member of the Garner Formation, and the town of Whitt in Parker County has the only public supply system that taps this source. Numerous domestic and livestock wells utilize ground water from both the Cisco and Strawn Groups.

Antlers Formation

The Antlers Formation is the lateral equivalent of the Twin Mountains and Paluxy Formation. In the northwestern part of the study region, north of the updip limit of the Glen Rose Formation (Figure 16), the elastic sand and clay of the Twin Mountains and Paluxy Formarions coalesce to form a single unit, the Antlers Formation (Figure 36 and 37).

The Antlers crops out mainly in Cooke, Montague, and Wise Counties. The Antlers dips to the southeast at an average rate of 20 feet per mile (3.8 m/km) near its outcrop to 70 feet per mile (13.3 m/km) near its southeastern limit. In parts of Grayson County on the south flank of the Preston anticline, the dip is southward in excess of 300 feet per mile (56.8 m/km).

A typical section of Antlers consists of a basal conglomerate and gravel overlain by a fine white to gray, poorly consolidated sand in massive-crossbedded layers interbedded with layers of red, purple, or gray clay in discontinuous lenses scattered throughout the formation. A middle section of Antlers contains considerably more clay beds than the upper or lower sections, and to the south, near the updip limit of the Glen Rose Formation, limestone beds also occur. Massive beds near the base and top of the Antlers probably correspond to the Twin Mountains and Paluxy Formations in the southern part of the study area. Fine white to yellow pack sand with thin beds of multicolored clay resting on a basal layer of gravel characterize a section on the outcrop.

Total thickness of the Antlers varies from about 400 feet (122 m) near the outcrop to about 900 feet (274 m) near the updip limit of the Glen Rose Limestone in southeast Grayson County. Well HA-19-22-704 in Cooke County shows a total thickness of 550 feet (167 m) while well KT-18-28-404 in Grayson County reveals a total thickness of 870 feet (265 m). The thickness gradually increases from west to east as illustrated on Figure 38. The approximate altitude of the top of the Antlers is shown on Figure 18.

Twin Mountains Formation

The Twin Mountains Formation outcrops in the western part of the study region in Hood, Parker, and Wise Counties. The Twin Mountains overlies Paleozoic rocks throughout the study region and is the lower member of the Trinity Group. The Twin Mountains underlies the Glen Rose Formation where the Glen Rose is present. In Wise, Denton, Cooke, and Grayson Counties, where the Glen Rose is absent, the Twin Mountains is equivalent to the lower unit of the Antlers Formation.

Originally the basal Cretaceous bed was named the Travis Peak Formation, but the name was changed to the Twin Mountains Formation in north-central Texas (Fisher and Rodda, 1966). The Travis Peak contains conglomerates of pebble-size and cobble-size limestone and dolomite, calcareous sands and silts, and impure limestones in central Texas. In contrast, the Twin Mountains sequence in north-central Texas consists mainly of medium- to coarse-grained sands, red and gray silty clays, and siliceous conglomerates of chert, quartzite, and quartz pebbles.

The Twin Mountains consists of a basal conglomerate of chert and quartz, grading upward into coarse- to fine-grained sand interspersed with varicolored shale. The sand strata are more thickly bedded in the lower part of the formation than in the upper and middle and can be correlated to the Hosston Formation to the south. It is in this lower massive sand that the majority of wells are completed. Varicolored shale and clay, predominantly red, occur throughout the formation. The shale grades vertically and laterally into sandy shale and sand, making correlations over long distances almost impossible. The upper part of the Twin Mountains also contains a considerable percentage of sand and sandstone strata but less than the lower part due to the increased interbedding of shale and clay. Few wells are developed in the upper part of the formation.

Beds dip toward the east from 30 feet per mile (5.7 m/km) near the outcrop to 95 feet per mile (18 m/km) near the downdip limit of fresh to slightly saline water as illustrated on the geologic cross sections and Figure 19 which shows the approximate altitude of the top of the Twin Mountains. Thickness varies considerably over the study region, generally increasing downdip and ranging from less than 200 feet (61 m) near the outcrop to 860 feet (262 m) in oil test HR-33-28-401. However, data on cross section C-C' (Figure 37) indicate that maximum thickness at the downdip limit of fresh to slightly saline water should reach approximately 1,000 feet (305 m).

The Twin Mountains Formation is the most important source of ground water for a large part of the study region anc yields moderate to large quantities of fresh to slightly saline water to municipal and industrial wells. In 1974, over 41,000 acre-feet (50.6 hm^3) of water was pumped from this aquifer for municipal and industrial uses.

Paluxy Formation

The Paluxy Formation is the upper member of the Trinity Group south of the Glen Rose pinch-out. It crops out in Hood, Parker, Tarrant, and Wise Counties and forms the surface of the Western Cross Timbers belt. The dip is easterly at an average rate of 30 feet per mile (5.7 m/km) near the outcrop, increasing to 80 feet per mile (15.2 m/km) near the downdip limit of fresh to slightly saline water as illustrated on the geologic sections and on Figure 18, which shows the approximate altitude of the top of the Paluxy and the extent of the outcrop in the study area.

The Paluxy is composed predominantly of fine- to coarse-grained, friable, homogeneous, white quartz sand interbedded with sandy, silty, calcareous, or waxy clay and shale. In general, coarse-grained sand is in the lower part. The Paluxy grades upward into fine-grained sand with variable amounts of shale and clay. The sands are usually well sorted, poorly cemented, and crossbedded. Pyrite and iron nodules are often associated with the sands and frequently contribute a red stain to the individual beds. In some areas along the outcrop, high iron concentrations are present in ground-water analyses.

Thickness of the Paluxy varies considerably throughout the study region. From a maximum thickness nearing 400 feet (122 m) in the northern part of the study area, the Paluxy thins to the south and southeast to less than 100 feet (30 m) with a net sand thickness of less than 40 feet (12 m). This thickness change is shown on the geologic sections and on Figure 20, which shows the approximate net thickness of sand and the downdip limit of fresh to slightly saline water.

The Paluxy Formation is an important aquifer in the study region and during 1974, produced over 10,000 acre-feet (12.3 hm^3) of water for municipal and industrial use and provided water to many domestic and livestock wells. Water wells tapping the Paluxy aquifer yield small to moderate quantities of fresh to slightly saline water.

Woodbine Group

The Woodbine Group is the basal rock unit of the Gulf Series of Cretaceous age in the study area. It crops out in Cooke, Dallas, Denton, Grayson, Johnson, and Tarrant Counties with a northeast-southwest strike. In the northern part of Texas, the outcrop parallels the Red River in a west-east strike, cropping out in Fannin, Lamar, and Red River Counties (Figure 16). The regional dip is to the southeast at an average rate of 35 feet per mile (6.63 m/km) near the outcrop and up to 75 feet per mile (14.2 m/km) near the downdip limit of fresh to slightly saline water as illustrated on the geologic sections and on Figure 21, which shows the approximate altitude of the top of the Woodbine.

In the southern part of the study area, the Woodbine is composed of friable, ferruginous, fine-grained sand and sandstone with interbedded shale, sandy shale, and laminated clay. The upper part of the Woodbine displays a marked increase in shale and clay, while the lower portion exhibits a more sandy make-up. Ripple marks and large-scale crossbedding are prevalent throughout the entire Woodbine Group.

In the northern part of the study area, the Woodbine is generally divided into a lower, middle, and upper part, which drillers refer to as first, second, and third Woodbine. These three parts can be readily distinguished on individual electric logs of wells located between Dallas and Sherman but are difficult to trace accurately as a unit over long distances along the strike or in the downdip area.

The upper Woodbine is mostly a fine-grained, well sorted, crossbedded, reddish-brown sandstone with concretions and some gray shale. The middle Woodbine is a reddish sandstone with interbedded gray to brown clay and some shale. The lower Woodbine is an interbedded, red-brown to white sandstone (sometimes exhibiting massive beds) with ironstone and sandy, gray to brown clay. It yields the largest quantity of water that is low in dissolved iron. The upper Woodbine yields I imitec amounts of water that contains large concentrations of iron.

The total thickness of the Woodbine ranges from 230 feet (70 m) near the southern extent of the outcrop to about 700 feet (213 m) near the downdip limit of fresh to slightly saline water in Fannin County. Regionally, the formation thickens downdip and toward the northeast. The change in thickness is shown on the geologic sections and on Figure 22, which shows the approximate net thickness of sand containing fresh to slightly saline water.

The Woodbine Group is an extremely important aquifer over a large portion of the study area, yielding over 8,500 acre-feet (10.5 hm^3) per year of water to public supply wells in nine of the 20 counties in this study.

Blossom Sand

The Blossom Sand of the Austin Group crops out in central Fannin, Lamar, and Red River Counties. The strike of the outcrop is east-west and ends in central Fannin County where the Blossom merges laterally into marl and chalk. The outcrop extends out of the study area into Bowie County to the east. The occurrence of usable quality water in the Blossom is generally limited to the Red River basin and the northern part of the Sulfur River basin. The dip is to the south averaging about 85 feet per mile (16.1 m/km).

The Blossom Sand consists of brown to light gray, unconsolidated, glauconitic, ferruginous, fine to medium sand interbedded with sandy and chalky marl. Most of the formation contains impermeable sandy clay or marl and chalk, with only about 25 percent sand. The amount of sand decreases westward near the town of Bonham.

The Blossom thickens southward downdip and eastward along the strike. Total thickness varies from zero in central Fannin County to about 400 feet (122 m) in southern Red River County. In some areas, the sand beds at the top and base of the formation approach a thickness of 50 feet (15 m). However, due to the impervious nature of the intervening beds, the sands are probably not hydrologically connected.

Nacatoch Sand

The Nacatoch Sand of the Navarro Group crops out in Delta, Hunt, Kaufman, Lamar, Navarro, and Red River Counties within the study region. It dips southward at about 80 feet per mile (15.2 m/km). In the western part of the outcrop, numerous faults of the Luling-Mexia-Talco fault system cut the formation.

The Nacatoch Sand consists of light gray, unconsolidated, massive, glauconitic, calcareous sand and marl. Approximately half of the formation is composed of sand, but individual beds vary considerably in extent and thickness laterally.

Thickness of the Nacatoch varies from 500 feet (152 m) in the eastern part of Red River County, decreasing westward along the strike, to about 350 feet (107 m) in parts of Delta and Hunt Counties. There is little change in thickness from the outcrop to the downdip limit of fresh to slightly saline water.

CHEMICAL QUALITY OF GROUND WATER AS RELATED TO USE

General Chemical Quality of Ground Water

All ground water contains minerals carried in solution, the type and concentration of which depend upon the surface and subsurface environment, rate of ground-water movement, and source of the ground water. Precipitation is relatively free of minerals until it comes in contact with the various constituents which make up the soils and component rocks of the aquifer. As a result of the water's solvent power, minerals are dissolved and carried into solution as the water moves through the aquifer. The concentration depends upon the solubility of the minerals present, the length of time water is in contact with the rocks, and the amount of dissolved carbon dioxide the water contains.

Concentrations of dissolved minerals in ground water generally increase with depth where circulation has been restricted due to various geologic conditions. Restricted circulation retards the flushing action of the fresh water moving through the aquifers, causing the water to become highly mineralized. In addition to natural mineralization, man can adversely alter the chemical quality of ground water by permitting highly mineralized water to enter fresh-water strata through inadequately constructed wells, by seepage from oil-field brine disposal pits, and disposal of animal wastes, sewage, or various industrial waste into fresh-water strata or into aquifer recharge areas.

The principal chemical constituents found in ground water are calcium, magnesium, sodium, iron, carbonate, bicarbonate, sulfate, chloride, and minor amounts of silica, potassium, manganese, nitrate, fluoride, and boron. Concentrations of these ions or chemical constituents are commonly reported in milligrams per liter (mg/l). The source, significance, and range in concentration of mineral constituents and properties of natural waters for the various aquifers in the study area are given in Table 2. Chemical analyses of water from selected wells in the study region are given in Table 4, Volume 2. Figure 23 shows the sulfate, chloride, and dissolved-solids content in water from selected wells in the Trinity and Woodbine aquifers.

Salt water is produced from oil and gas fields mainly in the norlhern half of the study area. Oil and gas wells which are not properly cemented opposite fresh to slightly saline water-producing formations and improper disposal of salt water can cause contamination of water-supply sources. Presently the area between Springtown in Parker County, and Decatur in Wise County, is experiencing apparently contaminated water in wells due to the improper completion of existing oil and gas wells. The main problem with this type of contamination is that the water may remain polluted long after the source of contamination is removed due to the slow rate of movement exhibited by ground water. Checks to insure continued good quality of ground water are now being made through a network of wells periodically sampled in each water-bearing formation. Comparisons of the relative concentrations of chemical constituents in native ground water, apparently contaminated ground water, and a typical oil-field brine are illustrated on Figure 5.

Quality Criteria or Standards

The degree and type of mineralization of ground water determines its suitability for municipal, industrial, irrigation, and other uses. Several criteria for water-quality requirements have been developed through the years which serve as guidelines in determining the suitability of water for various uses. Subjects covered by the guidelines are bacterial content; physical characteristics, including color, taste, odor, turbidity, and temperature; and the chemical constituents. Water-quality problems associated with the first two subjects can usually be alleviated economically. The neutralization or removal of most of the unwanted chemical constituents is usually difficult and often very costly.

Total dissolved-solids content is usually the main factor which limits or determines the use of ground water. Winslow and Kister (1956, p. 5) used an excellent, and very applicable, general classification of waters based on the dissolved-solids concentration in parts per million (ppm). The classification is as follows:

Description	Dissolved-Solids Content (ppm)
Fresh	Less than 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	More than 35,000

In recent years, most laboratories have begun reporting analyses in mlg/l (milligrams per liter) instead of ppm. These units, for practical purposes, are identical unless the dissolved-solids concentration of water reaches or exceeds 7,000 units (ppm or mg/l). The concentrations of chemical constituents reported in this report, other than for oil-field brines, are in mg/l (Tables 8, IO, 12, and 14). Most of the chemical concentrations are below 7,000 mg/l and therefore the units are interchangeable. For the more highly mineralized waters, a density correction should be made using the following formula:

$$\text{parts per million} = \frac{\text{milligrams per liter}}{\text{specific gravity of the water}}$$

Municipal

As the first step in setting national standards for drinking water quality under the provisions of the Safe Drinking Water Act of 1974, the U.S. Environmental Protection Agency (1975) issued drinking water regulations on December 10, 1975. These standards

Table 2.—Source, Significance, and Range in Concentration of Dissolved-Mineral Constituents and Properties of Water

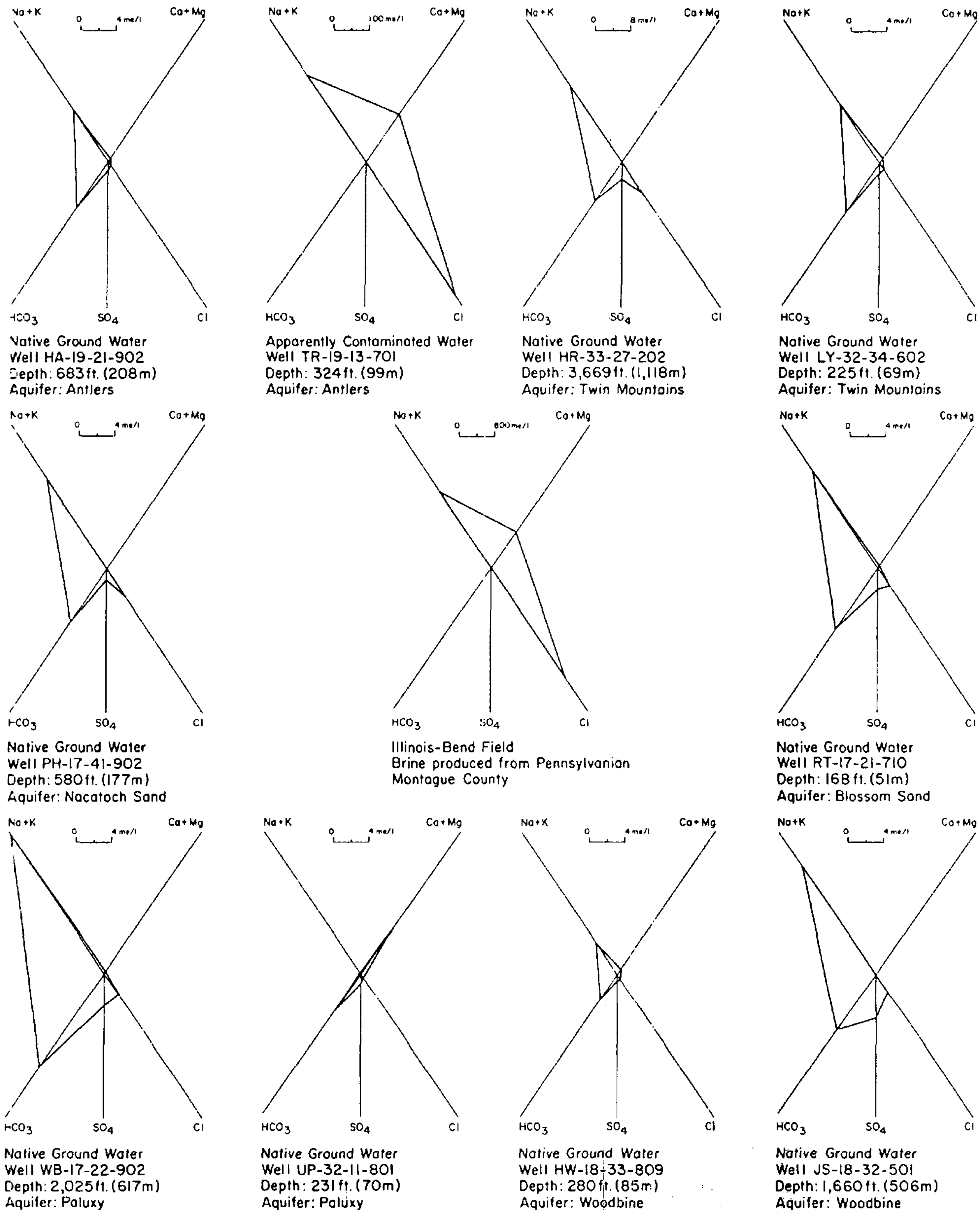
(Adapted from Doll and others, 1963, p. 39-43)

Only analyses representative of native ground water were used. Analyses are in mg/l except percent sodium, specific conductance, pH, and SAR.

Constituent or property	Source or cause	Significance	Range in concentrations, by aquifer: Antlers	Paluxy	Twin Mountains	Woodbine	Blossom	Nacatoch
Silica (SiO_2)	Dissolved from practically all rocks and soils, commonly less than 30 mg/l. High concentrations, as much as 100 mg/l, generally occur in highly alkaline waters.	Forms hard scale in pipes and boilers. Carried over in steam of high pressure boilers to form deposits on blades of turbines. Inhibits deterioration of zeolite-type water softeners.	3 – 72	1 – 76	0 – 102	0 – 79	3 – 13	5 – 65
Iron (Fe)	Dissolved from practically all rocks and soils. May also be derived from iron pipes, pumps, and other equipment.	On exposure to air, iron in ground water oxidizes to reddish-brown precipitate. More than about 0.3 mg/l stain laundry and utensils reddish-brown. Objectionable for food processing, textile processing, beverages, ice manufacture, brewing, and other processes. Texas Department of Health (1977) drinking water standards state that iron should not exceed 0.3 mg/l. Larger quantities cause unpleasant taste and favor growth of iron bacteria.	0 – 58.5	0 – 10.0	0 – 17.2	0 – 26.9	0 – .2	0 – .1
Calcium (Ca) and Magnesium (Mg)	Dissolved from practically all soils and rocks, but especially from limestone, dolomite, and gypsum. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water.	Cause most of the hardness and scale-forming properties of water, soap consuming (see hardness). Waters low in calcium and magnesium desired in electroplating, tanning, dyeing, and in textile manufacturing.	0 – 256 and 0 – 142	0 – 250 and 0 – 205	0 – 286 and 0 – 82	0 – 405 and 0 – 89	2 – 16 and 1 – 3	1 – 16 and 0 – 9
Sodium (Na) and Potassium (K)	Dissolved from practically all rocks and soils. Found also in oil field brines, sea water, industrial brines, and sewage.	Large amounts, in combination with chloride, give a salty taste. Moderate quantities have little effect on the usefulness of water for most purposes. Sodium salts may cause foaming in steam boilers and a high sodium content may limit the use of water for irrigation.	7 – 580 and [illegible] – 22.5	5 – 1,050 and 1 – 10.0	5 – 760 and 0 – 20.0	5 – 1,390 and [illegible] – 20.0	49 – 813 and 3.4 – 4.9	9 – 663 and [illegible] – 10.0
Bicarbonate (HCO_3) and Carbonate (CO_3)	Action of carbon dioxide in water on carbonate rocks such as limestone and dolomite.	Bicarbonate and carbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot water facilities to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium, cause carbonate hardness.	(HCO_3) 54 – 790	(HCO_3) 122 – 822	(HCO_3) 35 – 700	(HCO_3) 40 – 1,210	(HCO_3) 123 – 764	(HCO_3) 21 – 740
Sulfate (SO_4)	Dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Commonly present in some industrial wastes.	Sulfate in water containing calcium forms hard scale in steam boilers. In large amounts, sulfate in combination with other ions gives bitter taste to water. Texas Department of Health (1977) drinking water standards recommend that the sulfate content should not exceed 300 mg/l.	10 – 600	4 – 1,711	4 – 940	3 – 1,460	52 – 450	0 – 320
Chloride (Cl)	Dissolved from rocks and soils. Present in sewage and found in large amounts in oil field brines, sea water, and industrial brines.	In large amounts in combination with sodium, gives salty taste to drinking water. In large quantities, increases the corrosiveness of water. Texas Department of Health (1977) drinking water standards recommend that the chloride content should not exceed 300 mg/l.	7 – 590	0 – 616	3 – 980	4 – 1,833	29 – 762	6 – 580
Fluoride (F)	Dissolved in small to minute quantities from most rocks and soils. Added to many waters by fluoridation of municipal supplies.	Fluoride in drinking water reduces the incidence of tooth decay when the water is consumed during the period of enamel calcification. However, it may cause mottling of the teeth, depending on the concentration of fluoride, the age of the child, amount of drinking water consumed, and susceptibility of the individual (Maier, 1950, p. 1120-1132).	0 – 4.2	0 – 9.0	0 – 18.0	0 – 7.9	3 – 2.6	0 – 3.0
Nitrate (NO_3)	Decaying organic matter, sewage, fertilizers, and nitrates in soil.	Concentration much greater than the local average may suggest pollution. Texas Department of Health (1977) drinking water standards suggest a limit of 45 mg/l (as NO_3) or 10 (as N). Waters of high nitrate content have been reported to be the cause of methemoglobinemia (an often fatal disease in infants) and therefore should not be used in infant feeding (Maxcy, 1950, p. 271). Nitrate shown to be helpful in reducing inter-crystalline cracking of boiler steel. It encourages growth of algae and other organisms which produce undesirable tastes and odors.	0 – 90	0 – 133	0 – 170	0 – 994	2 – 4.2	0 – 11.0

Table 2.—Source, Significance, and Range in Concentration of Dissolved-Mineral Constituents and Properties of Water—Continued

Constituent or property	Source or cause	Significance	Range in concentrations, by aquifer: Antlers	Paluxy	Twin Mountains	Woodbine	Blossom	Nacatoch
Boron (B)	A minor constituent of rocks and of natural waters.	An excessive boron content will make water unsuitable for irrigation. Wilcox (1955, p. 11) indicated that a boron concentration of as much as 1.0 mg/l is permissible for irrigating sensitive crops, as much as 2.0 mg/l for semitolerant crops; and as much as 3.0 mg/l for tolerant crops. Crops sensitive to boron include most deciduous fruit and nut trees and navy beans; semitolerant crops include most small grains, potatoes and some other vegetables, and cotton; and tolerant crops include alfalfa, most root vegetables, and the date palm.	.2 - 1.3	0.2 - 3.0	0.1 - 1.9	0 - 5.7		0.4 - 0.9
Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils.	Texas Department of Health (1977) drinking water standards recommend that waters containing more than 1,000 mg/l dissolved solids not be used if other less mineralized supplies are available. For many purposes the dissolved-solids content is a major limitation on the use of water. A general classification of water based on dissolved-solids content, in mg/l, is as follows (Winslow and Kister, 1956, p. 5): Waters containing less than 1,000 mg/l of dissolved solids are considered fresh; 1,000 to 3,000 mg/l, slightly saline; 3,000 to 10,000 mg/l, moderately saline; 10,000 to 35,000 mg/l, very saline; and more than 35,000 mg/l, brine.	208 - 1,870	200 - 3,008	133 - 2,002	72 - 3,494	182 - 2,031	87 - 1,711
Hardness as $CaCO_3$	In most waters nearly all the hardness is due to calcium and magnesium. All of the metallic cations other than the alkali metals also cause hardness.	Consumes soap before a lather will form. Deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness in excess of this is called non-carbonate hardness. Waters of hardness up to 60 mg/l are considered soft; 61 to 120 mg/l, moderately hard; 121 to 180 mg/l, hard; more than 180 mg/l, very hard.	1 - 1,160	2 - 1,400	[illegible] - 914	0 - 940	6 - 47	2 - 56
Sodium-adsorption ratio (SAR)	Sodium in water.	A ratio for soil extracts and irrigation waters used to express the relative activity of sodium ions in exchange reactions with soil (U.S. Salinity Laboratory Staff, 1954, p. 72, 156). Defined by the following equation: $$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$$ where Na^{+}, Ca^{++}, and Mg^{++} represent the concentrations in milliequivalents per liter (me/l) of the respective ions.	.1 - 98.1	.1 - 85.6	.2 - 73.2	.2 - 129.5	3.1 - 117.2	.1 - 75.0
Residual sodium carbonate (RSC)	Sodium and carbonate or bicarbonate in water.	As calcium and magnesium precipitate as carbonates in the soil, the relative proportion of sodium in the water is increased (Eaton, 1950, p. 123-133). Defined by the following equation: $$RSC = (CO_3^{--} + HCO_3^{-}) - (Ca^{++} + Mg^{++})$$ where CO_3^{--}, HCO_3^{-}, Ca^{++}, and Mg^{++} represent the concentrations in milliequivalents per liter (me/l) of the respective ions.	0 - 13.8	0 - 132	0 - 11.1	0 - 19.2	1.1 - 12.6	0 - 11.8
Specific conductance (micromhos at 25°C)	Mineral content of the water.	Indicates degree of mineralization. Specific conductance is a measure of the capacity of the water to conduct an electric current. Varies with concentration and degree of ionization of the constituents.	338 - 2,646	345 - 5,240	207 - 4,030	109 - 6,080	315 - 3,690	527 - 2,480
Hydrogen ion concentration (pH)	Acids, acid-generating salts, and free carbon dioxide lower the pH. Carbonates, bicarbonates, hydroxides, phosphates, silicates, and borates raise the pH.	A pH of 7.0 indicates neutrality of a solution. Values higher than 7.0 denote increasing alkalinity; values lower than 7.0 indicate increasing acidity. pH is a measure of the activity of the hydrogen ions. Corrosiveness of water generally increases with decreasing pH. However, excessively alkaline waters may also attack metals. The Texas Department of Health (1977) recommends a pH greater than 7.	6.1 - 9.4	6.6 - 10.4	6.8 - 9.3	6.1 - 9.4	7.6 - 8.9	6.2 - 9.1
Percent Sodium	Sodium in water.	A ratio (using me/l) of the sodium ions to the total sodium, calcium, and magnesium ions. A percent Na exceeding 50 percent is a warning of a sodium hazard. Continued irrigation with this type of water will impair the tilth and permeability of the soil.	5.2 - 100	2.1 - 100	[illegible] - 100	3.8 - 100	70.0 - 99.5	34.4 - 99.8



Distance along each axis shows concentration of ions (in milliequivalents per liter) expressed as a percentage of the total concentration of dissolved solids.

Figure 5

Diagrams of Chemical Analyses of Ground Water and a Typical Oil-Field Brine apply to all of the public water systems of Texas and became effective June 1977. The responsibility for enforcement of these standards was assumed by the Texas Department of Health on July 1, 1977. Minor revision of the standards became effective on November 30, 1977.

As defined by the Texas Department of Health, municipal systems are classified as follows:

1. A "public water system" is any system for the delivery to the public of piped water for human consumption, if such a system has 4 or more service connections or regularly serves at least 25 individuals daily at least 60 days out of the year.

2. A "community water system" is any system which serves at least 4 or more service connections or regularly serves 25 permanent type residents for at least 180 days per year.

3. A "non-community water system" is any public water system which is not a community water system.

Standards which relate to municipal supplies are of two types: (1) primary and (2) secondary. Primary standards are devoted to constituents and regulations affecting the health of consumers. Secondary standards are those which deal with the esthetic qualities of drinking water. Contaminants for which secondary maximum contaminant levels are set in these standards do not have a direct impact on the health of the consumers, but their presence in excessive quantities may discourage the use of the water.

Primary Standards

Primary standards for dissolved minerals apply to community water systems and are as follows:

Contaminant	Maximum concentration (mg/l)
Arsenic (As)	0.05
Barium (Ba)	1 .o
Cadmium (Cd)	.OIO
Chromium (Cr6)	.05
Lead (Pb)	.05
Mercury (Hg)	.002
Selenium (Se)	.OI
Silver (Ag)	.05
Nitrate (as NO_3)	45
Nitrate (as N)	10

Except for nitrate content, none of the above contaminant levels for toxic minerals applies to non-community water systems. The maximum of 10 mg/l nitrate as nitrogen (about 45 mg/l nitrate as NO_3) applies to community and non-community systems alike.

Maximum fluoride concentrations are applicable to community water systems and they vary with the annual average of the maximum daily air temperature at the location of the system. These are shown in the following tabulation:

Temperature (°F)	Ternperature (°C)	Maximum concentration (mg/l)
63.9 to 70.6	17.7 to 21.4	1.8
70.7 to 79.2	21.5 to 26.2	1.6
79.3 to 90.5	26.3 to 32.5	1.4

Maximum contaminant limits for organic chemicals, as specified, apply to community water systems and are as follows:

Constituent	Maximum concentration (mg/l)
1. Chlorinated hydrocarbons:	
Endrin (1,2,3,4,10, 10-hexachloro-6,7,-epoxy-1,4,4a,5,6, 7,8,8a-octahydro-1,4-endo, endo-5, 8-dimethano napthalene).	0.0002
Lindane (1,2,3,4,5,6 hexachloro-cyclohexane, gamma isomer).	.004
Methoxychlor (I,1 ,I-Trichloro-2,2-bis [p-methoxyphenyl] ethane).	.I
Toxaphene ($C_{10}H_{10}$ &Cl_8-Technical chlorinated camphene, 67-69 percent chlorine).	005
2. Chlorophenoxys:	
2,4-D (2,4-Dichlorophenoxyacetic acid).	.I
2,4,5-TP Silvex (2,4,5-Trichlorophenoxypropionic acid).	.01

Maximum levels for coliform bacteria, as specified by the Texas Department of Health, apply to community and non-community water systems. The limits specified are basically the same as in the 1962 Public Health Service Standards which have been widely adopted in most states.

In addition to the previously stated requirements, there are also stringent rules regarding general sampling and the frequency of sampling which apply to all public water systems. Additionally, community water systems are subject to rigid radiological sampling and analytical requirements.

Secondary Standards

Recommended secondary standards applicable to all public water systems are given in the following table:

Constituent	*Maximum level*
Chloride (Cl)	300 mg/l
Color	15 color units
Copper (Cu)	1 .0 mg/l
Corrosivity	non-corrosive
Foaming agents	.5 mg/l
Hydrogen sulfide (H_2S)	.05 mg/l
Iron (Fe)	.3 mg/l
Manganese (Mn)	.05 mg/l
Odor	3 Threshold Odor Number
pH	> 7.0
Sulfate (SO_4)	300 mg/l
Dissolved solids	1,000 mg/l
Zinc (Zn)	5.0 mg/l

The above secondary standards are recommended limits, except for water systems which are not in existence as of the effective date of these standards. For water systems which are constructed after the effective date, no source of supply which does not meet the recommended secondary standards may be used without written approval by the Texas Department of Health. The determining factor will be whether there is an alternate source of supply of acceptable chemical quality available to the area to be served.

After July 1, 1977, for all instances in which drinking water does not meet the recommended limits and is accepted for use by the Texas Department of Health, such acceptance is valid only until such time as water of acceptable chemical quality can be made available at reasonable cost to the area in question from an alternate source. At such time, either the water which was previously accepted would have to be treated to lower the constituents to acceptable levels, or water would have to be secured from the alternate source.

Domestic and Livestock

Ideally, waters used for rural domestic purposes should be as free of contaminants as those used for municipal purposes; however, this is not economically possible. At present, there are no controls placed on private domestic or livestock wells. In general, the chemical constituents of waters used for domestic purposes should not exceed the concentrations shown in the following table, except in those areas where more suitable supplies are not available (Texas Department of Health, 1977).

Substance	Maximum concentration (mg/l)
Chloride (Cl)	300
Fluoride (F)	1.6 *
Iron (Fe)	.3
Manganese (Mn)	.05
Nitrate (as; N)	10
Nitrate (as NO_3)	45
Sulfate (SO_4)	300
Dissolved solids	1,000

'Maximum fluoride limit based on annual average of maximum daily air temperature range of 70.7 to 79.Z'F (21.5 to 26.2°C).

Many areas of north-central Texas do not have and cannot obtain domestic water supplies which meet the above recommended standards; however, supplies which do not meet these standards have been used for long periods of time without any apparent ill effects to the user. It is not generally recommended that water used for drinking purposes contain more than a maximum of 2,000 mg/l dissolved solids; however, water containing somewhat higher mineral concentrations has been used where water of better quality was not available.

Generall'y, water used for livestock purposes is subject to the same quality limitations as those relating to drinking water for humans; however, the tolerance limits of the v 8 a r s chemical constituents as well as the dissolved-solids concentration may be considerably higher for livestock than that which is considered satisfactory for human consumption. The type of animal, the kind of soluble salts, and the respective amount of soluble salts determine the tolerance limits (Heller, 1933, p. 22). In the western United States, cattle may tolerate drinking water containing nearly 10,000 mg/l dissolved solids providing these waters contain mostly sodium and chloride (Hem, 1970, p. 324). Waters containing high concentrations of sulfate are usually considered undesirable for livestock use.

Many investigators recommend an upper limit of dissolved solids near 5,000 mg/l as necessary for maximum growth and reproduction. Hem (1970, p. 324) cited a publication of the Department of Agriculture of the state of Western Australia as recommending the following maximum upper limits for dissolved-solids concentration in livestock water.

Animal	Maximum dissolved-solids concentration (mg/l)
Poultry	2,860
Hogs	4,290
Horses	6,435
Cattle (dairy)	7,150
Cattle (beef)	10,100
Sheep (adult)	12,900

Water having concentrations of chemical constituents in excess of the Texas Department of Health's standards may be objectionable for many reasons. Brief explanations for these objections, as well as the significance of each constituent, are given in Table 2.

Industrial

The chemical quality of ground water from the Cretaceous aquifers is generally favorable for industrial use throughout most of the study region. The tolerance in chemical quality of water for industrial use differs widely for different industries and different processes. Suggested water-quality tolerances are presented in Table 3.

Irrigation

The chemical composition of ground water is important in determining its usefulness for irrigation in that it should not adversely affect the productivity of the land. The extent to which chemical quality limits the suitability of ground water for irrigation depends on the nature, composition, and drainage of the soil and subsoil; the amounts of water used and methods of application; the kinds of crops grown; and the climate of the region, including the amounts and distribution of rainfall.

The characteristics of an irrigation water that seem to be most important in determining its quality are: 1) total concentration of soluble salts; 2) relative proportion of sodium to other principal cations (magnesium, calciurr, and potassium); 3) concentration of boron or other elements that may be toxic; and 4) under some conditions, the bicarbonate concentration as related to the concentration of calcium plus magnesium. These have been termed the salinity hazard, the sodium (alkali) hazard, the boron hazard, and the bicarbonate ion hazard (U.S. Salinity Laboratory Staff, 1954, p. 69-82; Wilcox, 1955, p. 11-12; and Lyerly and Longenecker, 1957, p. 13-15).

For purposes of diagnosis and classification, the total concentration of soluble salts (salinity hazard) in irrigation water can be adequately expressed in terms of specific conductance. Specific conductance is the measure of the ability of the ionized organic salts in solution to conduct an electrical current, and is usually expressed in terms of micromhos per centimeter at 25°C (77°F). In general, water having a conductance below 750 micromhos per centimeter is satisfactory for irrigation insofar as salt content is concerned, although salt-sensitive crops may be adversely affected by irrigation water having a conductance in the range of 250 to 750 micromhos per centimeter. Water in the range of 750 to 2,250 micromhos per centimeter is widely used, and satisfactory crop growth is obtained under good management (U.S. Salinity Laboratory Staff, 1954).

In the past, the sodium hazard had been expressed simply as the percent sodium and was divided into the following three classes: (a) water with a percent sodium less than 60, excellent to good; (b) water with a percent sodium between 60 and 75, good to injurious, and (c) water with a percent sodium greater than 75, injurious to unsatisfactory. A better measure of the sodium hazard of water for irrigation is the sodium-adsorption ratio (SAR) which is used to express the relative activity of sodium ions in exchange reactions with soil. The SAR is easily computed from the data determined in the usual water analysis by using the equation found in Table 2.

When the SAR and the specific conductance of a water are known, the classification of the water for irrigation can be determined by graphically plotting these values on the diagram shown in Figure 6. Low sodium water (SI) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. Medium-sodium water (S2) will present an appreciable sodium hazard in certain *fine-textured soils having high cation-exchange capacity* under low leaching conditions. This water may be used on coarse-textured or organic soils having good permeability. High-sodium water (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management. Very high sodium water (S4) is generally unsatisfactory for irrigation unless special action is taken, such as addition of gypsum

Table 3.--Water-Quality Tolerances for Industrial Application[1]

(Allowable Limits in Milligrams Per Liter Except as Indicated)

Industry	Turbidity	Color	Color $+O_2$ consumed	Dissolved oxygen (ml/l)	Odor	Hardness	Alkalinity (as $CaCO_3$)	pH	Total solids	Ca	Fe	Mn	Fe+Mn	Al_2O_3	SiO_2	Cu	F	CO_2	HCO_3	OH	$CaSO_4$	Na_2SO_4 to Na_2SO_3 ratio	General[2]
Air Conditioning[3]	--	--	--	--	--	--	--	--	--	--	0.5	0.5	0.5	--	--	--	--	--	--	--	--	--	A, B
Baking	10	10	--	--	--	(4)	--	--	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	C
Boiler feed:																							
0-150 psi	20	80	100	2	--	75	--	8.0+	3,000-1,000	--	--	--	--	5	40	--	--	200	50	50	--	1 to 1	--
150-250 psi	10	40	50	.2	--	40	--	8.5+	2,500-500	--	--	--	--	.5	20	--	--	100	30	40	--	2 to 1	--
250 psi and up	5	5	10	0	--	8	--	9.0+	1,500-100	--	--	--	--	.05	5	--	--	40	5	30	--	3 to 1	--
Brewing:[5]																							
Light	10	--	--	--	Low	--	75	6.5-7.0	500	100-200	.1	.1	.1	--	--	--	1	--	--	--	100-200	--	C, D
Dark	10	--	--	--	Low	--	150	7.0-	1,000	200-500	.1	.1	.1	--	--	--	1	--	--	--	200-500	--	C, D
Canning:																							
Legumes	10	--	--	--	Low	25-75	--	--	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	C
General	10	--	--	--	Low	--	--	--	--	--	.2	.2	.2	--	--	--	1	--	--	--	--	--	C
Carbonated beverages[6]	2	10	10	--	0	250	50	--	850	--	.2	.2	.3	--	--	--	.2	--	--	--	--	--	C
Confectionary	--	--	--	--	Low	--	--	(7)	100	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	--
Cooling[8]	50	--	--	--	--	50	--	--	--	--	.5	.5	.5	--	--	--	--	--	--	--	--	--	A, B
Food, general	10	--	--	--	Low	--	--	--	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	C
Ice (raw water)[9]	1-5	5	--	--	--	--	30-50	--	300	--	.2	.2	.2	--	10	--	--	--	--	--	--	--	C
Laundering	--	--	--	--	--	50	--	--	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	--
Plastics, clear, undercolored	2	2	--	--	--	--	--	--	200	--	.02	.02	.02	--	--	--	--	--	--	--	--	--	--
Paper and pulp:[10]																							
Groundwood	50	20	--	--	--	180	--	--	--	--	1.0	.5	1.0	--	--	--	--	--	--	--	--	--	A
Kraft pulp	25	15	--	--	--	100	--	--	300	--	.2	.1	.2	--	--	--	--	--	--	--	--	--	--
Soda and sulfite	15	10	--	--	--	100	--	--	200	--	.1	.05	.1	--	--	--	--	--	--	--	--	--	--
Light paper, HL-Grade	5	5	--	--	--	50	--	--	200	--	.1	.05	.1	--	--	--	--	--	--	--	--	--	B
Rayon (viscose) pulp:																							
Production	5	5	--	--	--	8	50	--	100	--	.05	.03	.05	< 8.0	< 25	< 5	--	--	--	--	--	--	--
Manufacture	.3	--	--	--	--	55	--	7.8-8.3	--	--	.0	.0	.0	--	--	--	--	--	--	--	--	--	--
Tanning[11]	20	10-100	--	--	--	50-135	135	8.0	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	--
Textiles:																							
General	5	20	--	--	--	20	--	--	--	--	.25	.25	--	--	--	--	--	--	--	--	--	--	--
Dyeing[12]	5	5-20	--	--	--	20	--	--	--	--	.25	.25	.25	--	--	--	--	--	--	--	--	--	--
Wool scouring[13]	--	70	--	--	--	20	--	--	--	--	1.0	1.0	1.0	--	--	--	--	--	--	--	--	--	--
Cotton bandage[13]	5	5	--	--	Low	20	--	--	--	--	.2	.2	.2	--	--	--	--	--	--	--	--	--	--

1/ American Water Works Association, 1950.
2/ A--No corrosiveness; B--No slime formation; C--Conformance to Federal drinking water standards necessary; D--NaCl, 275 mg/l.
3/ Waters with algae and hydrogen sulfide odors are most unsuitable for air conditioning.
4/ Some hardness desirable.
5/ Water for distilling must meet the same general requirements as for brewing (gin and spirits mashing water of light-beer quality; whiskey mashing water of dark-beer quality).
6/ Clear, odorless, sterile water for syrup and carbonization. Water consistent in character. Most high quality filtered municipal water not satisfactory for beverages.
7/ Hard candy requires pH of 7.0 or greater, as low value favors inversion of sucrose, causing sticky product.
8/ Control of corrosiveness is necessary as is also control of organisms, such as sulfur and iron bacteria, which tend to form slimes.
9/ Ca $(HCO_3)_2$ particularly troublesome. $Mg(HCO_3)_2$ tends to greenish color. CO_2 assists to prevent cracking. Sulfates and chlorides of Ca, Mg, Na should each be less than 300 mg/l (white butts).
10/ Uniformity of composition and temperature desirable. Iron objectionable as cellulose adsorbs iron from dilute solutions. Manganese very objectionable, clogs pipelines and is oxidized to permanganates by chlorine, causing reddish color.
11/ Excessive iron, manganese, or turbidity creates spots and discoloration in tanning of hides and leather goods.
12/ Constant composition; residual alumina 0.5 mg/l.
13/ Calcium, magnesium, iron, manganese, suspended matter, and soluable organic matter may be objectionable.

to the soil (Lyerly and Longenecker, 1957, p. 14-15). Low-salinity water (C1) can be used for irrigation of most crops on most soils with little likelihood that soil salinity will develop. Medium-salinity water (C2) can be used if a moderate amount of leaching occurs. High salinity water (C3) cannot be used on soils with restricted drainage. Very high-salinity water (C4) is not suitable for irrigation under ordinary conditions.

Boron is necessary for plant growth, but is highly toxic and unsuitable for irrigation at concentrations only slightly more than optimum. Scofield (1936, p. 286) suggests the following permissible limits of boron for irrigation water:

Classes of water

Rating	Grade	Sensitive crops (mg/l)	Semitolerant crops (mg/l)	Tolerant crops (mg/l)
1	Excellent	< 0.33	< 0.67	< 1.00
2	Good	.33 to .67	.67 to 1.33	1.00 to 2.00
3	Permissible	.67 to 1.00	1.33 to 2.00	2.00 to 3.00
4	Doubtful	1.00 to 1.25	2.00 to 2.50	3.00 to 3.75
5	Unsuitable	> 1.25	> 2.50	> 3.75

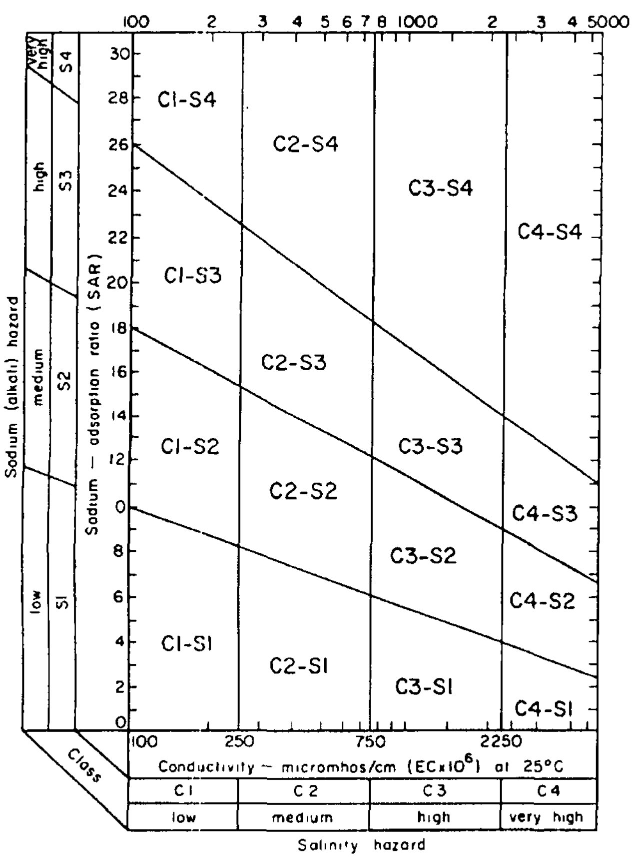


Figure 6.—Diagram for the Classification of Irrigation Waters (After United States Salinity Laboratory Staff, 1954, p. 80)

In water having high concentrations of bicarbonate, there is a tendency for calcium and magnesium to precipitate as the water in the soil becomes more concentrated. Due to this reaction, the relative proportion of sodium in the water is increased in the form of sodium carbonate. Using this residual sodium carbonate (RSC) concept, it was concluded by the U.S. Department of Agriculture that water having more than 2.50 milliequivalents per liter (me/l) RSC is not suitable for irrigation purposes. Water containing 1.25 to 2.50 me/l RSC is marginal, and water containing less than 1.25 me/l is safe. The method of calculating RSC is found in Table 2.

In appraising the quality of an irrigation water, first consideration must be given to salinity and sodium hazards. Then consideration should be given to independent characteristics such as boron and bicarbonate, either of which may change the quality rating. The use of water of any quality must take into account such factors as drainage and management practices.

Most irrigation wells in the study area are scattered over the Trinity and Woodbine outcrops with only a few areas of concentrated activity. Occasionally deeper wells are found downdip from the outcrop and are used primarily to irrigate golf courses. Approximately 5,000 acre-feet (6.17 hm^3) of water was pumped for irrigation purposes in 1977 from Cretaceous formations in the study area, with about 55 percent of the water from the Woodbine Group. The largest concentration of irrigation wells is located on the Woodbine outcrop in an area bounded by western Grayson County, the eastern edge of Cooke County, and the northeastern corner of Denton County. Approximately 80 irrigation wells operate in this area and several produce as much as 900 gpm (56.8 l/s). Several smaller irrigation well developments are located in Parker and Hood Counties (Twin Mountains) and in Wise County (Antlers). There are also irrigation wells in Fannin County producing from the alluvium along the Red River, but not enough water-quality data were collected for inclusion in this study.

OCCURRENCE AND DEVELOPMENT OF GROUND WATER

Antlers Formation

The Antlers combines the ground-water availablity of both the Paluxy and Twin Mountains Formations to the south (Table I). Small-capacity wells tap the upper part of the Antlers while large production wells pump from either the lower section or the entire aquifer.

The primary source of ground water in the Antlers Formation is precipitation on the outcrop. The average annual precipitation on the outcrop is about 32 inches (81.3 cm), and the mean annual temperature is about 64^{0}F (18^{0}C). Surface-water seepage from lakes and streams on the outcrop is also a source of ground water. Water in the outcrop area is unconfined and therefore under water-table conditions. Downdip from the outcrop, the water in confined under hydrostatic pressure and is under artesian conditions.

Recharge to the sandy portion of the 650 square miles (1,684 km^2) of Antlers outcrop is less than 1 inch (2.5 cm) of precipitation per year. The rate of movement of water through an aquifer depends upon the permeability, porosity, and hydraulic gradient. The average rate of movement of water in the Antlers is about 1 to 2 feet (0.3 to 0.6 m) per year (Baker, 1960, p. 37). Ground water moves slowly downdip in an east-southeast direction. Water-level measurements indicate the present gradient of the piezometric surface is 7 to 24 feet per mile (1.3 to 4.5 m/km) except for local fluctuations and around areas of heavy
In areas of heavy pumping, a cone of depression forms and the direction of ground-water movement is toward these points of discharge from all directions. Altitudes of water levels about 1955 and about 1976 are shown on Figures 24 and 25. Cones of depression can be seen around the cities of Gainesville and Sherman.

Wells tap the Antlers in the outcrop area of Montague and Wise Counties and in the downdip areas of Cooke, Denton, and Grayson Counties. Discharge from the Antlers occurs naturally through the pumpage of water wells. In 1976, approximately 10,760 acre-feet (13.3 hm^3) of water was pumped from the Antlers in this area.

Table 4 shows the results of pumping tests conducted in the study region, including the aquifer coefficients of storage, permeability, transmissibility, and specific capacities. The locations of the tests and the coefficients of transmissibility and permeability are shown on Figure 26. Test results were obtained from existing literature and data reported by well drillers. Permeability coefficients were computed by dividing the transmissibility of the well by its screened interval. Net sand thicknesses throughout the aquifer are illustrated on Figure 27..

Transmissibility values were considerably higher for wells tested in Cooke County than in Grayson County. Results of the eight tests conducted on wells in the vicinity of Gainesville showed a range of transmissibilities of 5,800 to 17,879 (gal/d)/ft, or 72,000 to 222,000 (l/s)/m, with an average value of 9,970 (gal/d)/ft, or 123,800 (l/s)/m. In contrast with this area, the range of transmissibilities of nine tests conducted in the Sherman vicinity was 1,860 to 4,727 (gal/d)/ft, or 23,100 to 58,700 (l/s)/m, with an average value of 3,735 (gal/d)/ft, or 46,400 (l/s)/m. Similarly, the coefficients of permeability around Gainesville averaged about 53 (gal/d)/ft^2, or 2,200 (l/s)/m^2 while in the Sherman area, the average was 24 (gal/d)/ft^2, or 978 (l/s)/m^2.

Only two coefficient of storage values, both in Sherman, were determined by the U.S. Geological Survey in 1945. An approximate value of 2.5 X 10^{-4} seems representative for this area. The average artesian storage coefficient was estimated by multiplying the average net saturated sand thickness, in feet, by 10^{-6} per foot, which is proper for most confined aquifers (Lohman, 1972, p. 8).

The specific yield of the Antlers is on the order of 20 to 25 percent as estimated by seismic methods (Duffin and Elder, 1979). The yields from the Antlers range from less than 20 (1.3 l/s) to 920 gal/min (58 l/s), with an average of 200 gal/min (13 l/s) for the 119 measured wells. Yields were highest around Gainesville and Sherman because these wells penetrate the total thickness of the aquifer and are screened opposite all

Table 4.—Results of Pumping Tests

Aquifer: Kca, Antlers Formation; Kcpa, Paluxy Formation; Kct, Trinity Group; Kctm, Twin Mountains Formation; Kgbl, Blossom Sand of Austin Group; Kgna, Nacatoch Sand of Navarro Group; Kgw, Woodbine Group.

Coefficient of transmissibility values shown are the averages from drawdown and recovery test data.

Well	Aquifer	Test Date	Screened from (ft)	Interval to (ft)	Yield (gal/min)	Coefficient of Transmissibility [(gal/d)/ft]	Coefficient of storage	Coefficient of Permeability [(gal/d)/ft²]	Specific Capacity [(gal/min)/ft]
				Collin County					
DT-18-44-202	Kgw	Apr. 6, 1976	1,300	1,526	150	1,885	–	17	1.1
50-501	Kctm	Sept. 18, 1953	2,266	2,515	1,940	20,683	–	83	11.3
502	do	Mar. 20, 1954	2,378	2,640	1,845	21,486	–	82	12.2
504	Kcpa	July 26, 1973	1,333	1,652	238	1,263	–	6	1.0
51-301	Kctm	Oct. 22, 1952	3,110	3,410	690	29,724	–	99	7.7
				Cooke County					
HA-19-23-401	Kca	Aug. 29, 1942	–	–	385	5,800	–	–	2.0
503	do	Aug. 23, 1942	660	910	340	9,250	–	44	5.0
		Aug. 17, 1960	660	910	580	12,303	–	67	5.0
805	do	Aug. 4, 1971	629	893	818	10,972	–	54	8.2
901	do	May 8, 1952	723	890	375	8,316	–	55	1.7
903	do	May 30, 1960	767	927	320	17,879	–	–	18.5
906	do	Mar. 5, 1965	754	961	800	6,414	–	43	3.7
31-302	do	Mar. 28, 1959	726	978	720	8,818	–	53	4.8
				Dallas County					
HR-33-01-301	Kctm	May 7, 1957	2,017	2,260	1,254	20,130	–	100	9.7
02-102	do	May 27, 1975	2,245	2,455	1,697	17,256	–	102	7.1
09-102	do	June 27, 1973	1,930	2,120	759	13,905	–	99	5.9
402	do	May 20, 1965	1,922	2,074	708	17,076	–	112	6.3
403	do	Apr. 3, 1972	1,924	2,077	754	12,141	–	80	6.2
507	do	Oct. 10, 1972	2,102	2,240	759	13,085	–	106	5.5
508	do	Jan. 14, 1972	1,999	2,145	703	17,718	–	124	7.7
701	do	May 4, 1965	1,880	2,039	708	8,400	–	53	6.1
908	Kcpa	Nov. 29, 1965	1,375	1,504	317	6,118	–	62	2.8
10-501	Kctm	Nov. 14, 1948	2,567	2,734	1,014	17,000	9×10^{-5}	102	–
805	do	Nov. 14, 1948	2,534	2,735	511	16,300	8×10^{-5}	81	4.1
831	Kcpa	Nov. 17, 1948	–	–	166	2,890	2×10^{-5}	–	0.7
17-115	Kctm	Oct. 19, 1953	1,900	2,065	480	12,500	2×10^{-4}	76	–
802	do	Mar. 31, 1969	2,394	2,518	638	3,660	–	31	2.8
18-201	do	Apr. 11, 1955	2,620	2,883	750	12,300	5×10^{-5}	47	–
803	do	Nov. 6, 1973	2,904	3,088	1,051	13,242	–	–	6.9
26-104	do	June 4, 1964	2,604	2,745	650	7,692	–	55	3.4
105	do	Aug. 5, 1968	2,644	2,814	715	10,397	–	61	4.1
27-205	do	Sept. 29, 1964	3,322	3,442	300	3,593	–	30	3.3
602	Kgw	June 1, 1965	1,288	1,352	170	4,700	–	78	4.2
				Delta County					
HU-17-42-806	Kgna	Oct. 14, 1965	422	525	200	2,300	–	29	1.0
807	do	Nov. 15, 1965	507	620	254	2,563	–	28	1.2
808	do	Dec. 8, 1965	425	525	200	2,151	–	26	1.0
				Denton County					
HW-18-33-703	Kca	May 10, 1957	1,372	1,514	167	4,900	–	35	–
57-602	Kctm	Nov. 19, 1974	2,235	2,390	795	12,369	–	–	10.2
19-47-901	Kctm, Kcpa	July 8, 1960	770	1,184	888	6,900	–	28	3.4
55-305	Kctm	Dec. 15, 1948	1,029	1,130	450	4,150	5×10^{-5}	46	–
56-101	do	Dec. 1, 1948	1,082	1,214	450	4,150	5×10^{-5}	23	–
103	do	Dec. 1, 1951	1,055	1,200	450	5,020	–	34	5.0
104	Kct	May 14, 1957	624	1,142	670	3,000	–	19	5.1
64-905	Kctm	Jan. 20, 1972	1,690	1,892	560	8,963	–	47	6.4
906	Kcpa	Mar. 27, 1972	853	944	236	5,197	–	84	0.7
32-07-205	Kctm	June 17, 1974	1,291	1,391	510	12,680	–	127	4.8

Table 4.—Results of Pumping Tests—Continued

Aquifer: Kca, Antlers Formation; Kcpa, Paluxy Formation; Kct, Trinity Group; Kctm, Twin Mountains Formation; Kgbl, Blossom Sand of Austin Group; Kgna, Nacatoch Sand of Navarro Group; Kgw, Woodbine Group.

Coefficient of transmissibility values shown are the averages from drawdown and recovery test data.

Well	Aquifer	Test Date	Screened from (ft)	Interval to (ft)	Yield (gal/min)	Coefficient of Transmissibility [(gal/d)/ft]	Coefficient of storage	Coefficient of Permeability [(gal/d)/ft²]	Specific Capacity [(gal/min)/ft]
				Ellis County					
JK-32-40-608	Kctm	Feb. 10, 1976	2,290	2,390	250	5,442	–	65	2.9
901	Kcpa	June 2, 1965	1,230	1,338	79	3,140	–	32	2.7
33-33-101	Kctm	June 6, 1965	2,175	2,335	450	5,900	–	39	3.0
34-702	do	Mar. 14, 1948	–	–	617	8,960	8×10^{-5}	–	2.6
703	do	do	–	–	504	8,800	9×10^{-5}	–	–
35-503	Kgw	June 2, 1965	1,330	1,390	120	11,300	–	183	3.9
41-203	Kctm	Jan. 25, 1975	2,410	2,540	160	16,547	–	165	3.1
49-602	Kgw	May 17, 1957	839	929	201 *	1,320	–	22	0.8
				Fannin County					
JS-18-31-201	Kgw	Aug. 1, 1957	1,096	1,240	740	14,000	–	75	9.3
39-702	do	June 23, 1975	1,464	1,606	300	1,371	–	14	3.8
				Grayson County					
KT-18-10-406	Kgw	Aug. 20, 1958	–	–	132	16,700	–	167	7.0
802	do	Aug. 15, 1958	189	345	145	7,870	–	84	2.2
11-802	do	Mar. 27, 1958	241	341	73	2,250	–	43	2.2
17-901	Kca	May 9, 1957	1,388	1,519	330	4,600	–	23	3.2
20-701	Kgw	July 14, 1945	721	788	249	2,400	–	42	–
702	do	do	725	776	260	2,190	9×10^{-5}	43	–
703	Kca	do	1,965	2,136	360	2,420	1×10^{-4}	17	–
704	Kgw	do	541	580	260	2,420	2×10^{-4}	22	–
705	do	do	726	785	260	2,320	1.9×10^{-4}	39	–
706	do	do	724	786	260	2,340	1.8×10^{-4}	38	–
709	Kca	do	1,382	2,084	360	3,440	2×10^{-4}	11	–
801	Kgw	Aug. 9, 1966	650	980	608	6,710	–	24	5.1
802	Kca	Jan. 17, 1967	1,510	2,214	567	4,288	–	11	3.4
804	Kgw	May 5, 1970	570	1,034	708	4,938	–	21	3.4
25-601	Kca	Apr. 8, 1957	1,355	–	110	4,500	–	23	4.2
27-801	Kgw	Oct. 10, 1973	630	934	554	2,389	–	14	2.1
802	Kca	Oct. 27, 1975	1,594	2,454	608	3,081	–	8	1.8
803	do	July 12, 1976	–	–	638	4,727	–	–	2.6
28-102	do	Jan. 28, 1959	1,590	2,420	602	4,690	–	97	3.5
103	Kgw	do	832	1,012	602	5,950	–	40	4.7
402	do	May 4, 1970	840	969	457	3,442	–	33	3.1
403	do	June 7, 1972	794	1,064	402	2,976	–	27	2.2
404	Kca	Mar. 8, 1972	1,700	2,450	510	1,860	–	5	3.4
702	Kgw	Apr. 21, 1954	908	1,054	105	7,920	–	78	2.0
29-902	do	Mar. 26, 1958	1,109	1,189	80	2,394	–	30	2.2
35-402	do	Mar. 24, 1958	655	730	52	14,700	–	178	1.5
36-502	do	July 31, 1957	1,165	1,400	250	7,900	–	99	2.7
503	Kca	July 29, 1970	2,010	2,290	250	1,100	–	6	0.6
				Hunt County					
PH-17-41-901	Kgna	Nov. 9, 1943	374	412	285	2,670	–	70	5.1
902	do	Nov. 7, 1943	375	435	285	2,660	–	44	9.3
				Johnson County					
PX-32-30-502	Kcpa	May 10, 1960	472	586	134	1,573	–	26	1.3
37-901	Kctm	Apr. 21, 1958	961	1,245	423	4,600	–	19	1.7
38-309	do	Jan. 8, 1969	1,135	1,425	164	1,948	–	8	–
901	do	Oct. 5, 1964	1,522	1,575	100	4,761	–	110	0.5
39-702	Kcpa, Kctm	May 4, 1947	766	1,634	296	4,568	–	26	2.8
45-302	Kctm	Feb. 19, 1945	898	1,204	472	4,509	–	43	2.6
304	do	Jan. 25, 1938	941	1,251	405	4,656	–	28	1.5
601	do	Apr. 12, 1955	895	1,165	560	7,400	–	31	2.8
47-802	Kcpa	Mar. 24, 1955	802	846	84	6,517	–	148	1.7
803	Kgw	Nov. 16, 1966	187	210	47	2,208	7×10^{-5}	56	–
806	do	do	182	204	47	1,837	–	84	1.0
54-101	Kctm	Dec. 6, 1966	1,137	1,215	168	4,247	–	55	1.8

Table 4.—Results of Pumping Tests—Continued

Aquifer: Kca, Antlers Formation; Kcpa, Paluxy Formation; Kct,
Trinity Group; Kctm, Twin Mountains Formation; Kgbl, Blossom Sand
of Austin Group; Kgna, Nacatoch Sand of Navarro Group;
Kgw, Woodbine Group.

Coefficient of transmissibility values shown are the averages from drawdown and recovery test data.

Well	Aquifer	Test Date	Screened from (ft)	Interval to (ft)	Yield (gal/min)	Coefficient of Transmissibility [(gal/d)/ft]	Coefficient of storage	Coefficient of Permeability [(gal/d)/ft²]	Specific Capacity [(gal/min)/ft]
				Red River County					
WB-17-24-803	Kgbl	Dec. 3, 1969	465	530	164	1,316	–	21	1.3
32-201	do	Aug. 9, 1960	523	600	630	4,100	6×10^{-5}	54	–
203	do	Aug. 10, 1960	510	602	630	3,690	3×10^{-5}	41	–
39-508	Kgna	Aug. 16, 1972	150	270	349	6,330	–	53	3.6
				Tarrant County					
XU-32-07-602	Kctm	May 15, 1972	1,500	1,573	602	6,667	–	92	4.1
13-701	Kcpa	Mar. 24, 1954	–	–	100	3,100	3.4×10^{-4}	–	–
703	do	do	–	–	–	7,500	–	72	3.3
901	do	May 27, 1955	–	–	60	4,100	7.4×10^{-5}	–	–
14-609	Kctm	Dec. 4, 1954	958	1,090	361	6,860	–	69	2.8
701	do	Dec. 3, 1953	867	964	247	3,250	6.2×10^{-5}	34	–
702	do	Aug. 12, 1954	855	952	236	2,900	7.6×10^{-5}	30	–
15-104	Kcpa	May 19, 1961	575	692	164	13,808	–	138	3.0
105	do	Apr. 26, 1961	434	549	107	2,934	–	28	1.3
207	do	Apr. 24, 1961	538	677'	101	1,536	–	18	0.7
15-401	Kcpa	Mar. 17, 1954	460	522	80	2,660	1.2×10^{-4}	37	0.7
412	Kctm	June 10, 1955	1,059	1,225	412	3,580	–	28	3.4
413	Kcpa	Aug. 1, 1961	511	624	105	3,126	–	35	2.0
507	Kctm	Jan. 12, 1965	1,232	1,428	717	9,756	–	60	6.4
512	do	June 9, 1966	1,219	1,350	708	9,147	–	70	4.0
601	do	Mar. 20, 1955	1,179	1,450	793	11,789	–	85	5.0
902	Kcpa	June 4, 1954	668	809	408	6,150	–	49	3.1
16-503	Kgw	Mar. 22, 1951	236	266	15	2,740	–	91	1.2
21-204	Kcpa	Aug. 11, 1962	280	375	107	3,312	–	42	1.3
405	do	Mar. 12, 1960	193	248	126	2,867	–	60	1.6
502	do	Mar. 25, 1960	209	270	105	2,164	–	48	1.4
22-601	do	Apr. 9, 1953	209	270	52	4,250	1.8×10^{-4}	–	–
702	do	Aug. 17, 1953	380	450	80	3,350	–	70	1.9
901	Kctm	June 18, 1972	1,108	1,335	455	6,231	–	47	4.5
907	Kcpa	June 19, 1965	507	580	108	10,937	–	150	2.7
909	Kctm	Aug. 1, 1966	1,042	1,280	556	8,925	–	72	4.7
910	Kcpa	July 31, 1962	488	586	125	2,005	–	25	1.2
23-101	Kctm	Aug. 21, 1945	1,154	1,334	260	11,000	6×10^{-5}	74	2.8
102	do	Nov. 7, 1950	1,180	1,340	768	8,837	–	59	3.9
103	do	Jan. 8, 1954	–	–	259	7,400	4×10^{-5}	37	3.9
104	do	Aug. 25, 1948	1,210	1,330	240	7,850	5×10^{-5}	65	2.5
106	do	do	1,239	1,359	473	10,000	–	83	3.4
108	do	Jan. 11, 1954	1,305	1,423	260	9,000	7×10^{-5}	95	–
401	do	Feb. 15, 1951	1,004	1,326	705	9,800	–	54	2.9
404	Kctm	Jan. 21, 1971	1,064	1,350	708	1,525	–	–	3.8
603	Kcpa	May 5, 1954	628	776	465	3,900	–	43	1.0
802	Kctm	May 26, 1966	1,408	1,580	503	16,795	–	125	4.6
24-101	do	Sept. 16, 1942	1,567	1,751	450	12,500	–	68	4.5
202	Kcpa	Feb. 26, 1954	888	1,058	402	6,300	–	45	3.2
31-605	Kctm	Apr. 2, 1955	1,592	1,708	390	6,700	–	69	2.7

fresh water-bearing sands. The specific capacity of a well is generally expressed as the ratio of the yield in gallons per minute (liters per second) to the drawdown in feet (meters). A word of caution must be used in comparing specific capacities of wells. The method of well completion is an important function of specific capacity. For example, a gravel-walled and screened well of the same diameter and in the same location as a well with either torch-slotted or gun-perforated casing would have a considerably higher specific capacity. Specific capacir es of 63 wells that obtain water from the Antlers Formation in the study region ranged from 0.3 to 8.5 (gal/min)/ft or 0.06 to 1.8 (l/s)/m, with an average of 2.7 (gal/min)/ft or 0.56 (l/s)/m.

Except for water levels in wells on or near the outcrop, static levels have been steadily declining over the years. Long-range declines have averaged up to 7 feet (2 m) per year, with as much as 10 ft/yr (3 m/yr) during recent measurements in developed areas. Figure 28 shows the approximate change in water levels in Antlers wells from about 1955 to about 1976. Hydrographs showing long-term water-level changes under water table and artesian conditions are illustrated by Figures 7 and 8.

Long-range declines in the water table seem to increase from west to east, parallel to the Red River in a line from Muenster in Cooke County, to Sherman in Grayson County. The water level in well HA-19-21-903 in Muenster declined 133 ft (41 m) in 37 years; well HA-19-23-905 in Gainesville declined 146 ft (45 m) in 40 years; well KT-18-17-902 in Whitesboro lowered 209 feet (64 m) in 42 years; and well KT-18-20-709 declined 228 ft (69 m) in 32 years. Along this strike, water levels have fallen from 3.6 ft/yr (1 m/yr) in western Cooke County to 7.1 ft/yr (2 mlyr) in central Grayson County. Wells outside the influence of large centers of pumpage also show declines but not near as severe, with deficits of only a few feet per year (less than one meter per year).

Water levels in the vicinity of Gainesville are near the top of the Antlers, while pumping levels there drop about 100 feet (30 m) below the top. The static level in a well at Era, in southern Cooke County, is 200 feet (61 m) below the top of the Antlers. Pumping levels in most of the large-capacity wells in Cooke County are below the top of the formation. However, due to the influence of the Preston anticline and the Sherman syncline, the top of the Antlers at the city of Sherman is about 1,480 feet (451 m) below land surface. Consequently, static water levels there are about 1,000 feet (305 m) above the top of the formation and pumping levels are about 700 feet (213 m) above the top of the Antlers.

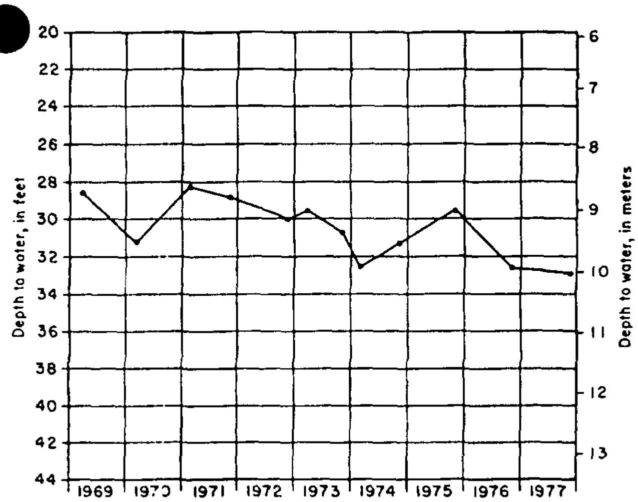
Of the estimated 82,000 acre-feet (101 hm^3) of water pumped from the Woodbine and Trinity Group aquifers in 1976, only 13 percent or 10,670 acre-feet (13.2 hm^3) was pumped from the Antlers. Most of this ground water is utilized for municipal purposes. About 70 percent of the large-capacity Antlers wells inventoried for this study were public supply wells and accounted for 77 percent of the total pumpage from the Antlers. Public supply pumpage increased from 4,920 acre-feet (6.07 hm^3) in 1955 to 8,260 acre-feet (10.2 hm^3) in 1976. The estimated amounts of ground water pumped from the Antlers for irrigation and for public supply and industrial purposes are shown in Tables 5 and 6. Domestic wells pumped an estimated 1,800 acre-feet (2.22 hm^3) of water from the Antlers in 1975.

The development of the Antlers as a public supply source began in the city of Sherman with a 2,300 foot (701 m) well located near well KT-18-20-715. It was drilled in 1889 and produced 200 gal/min (12.6 l/s). Sherman had two more deep wells drilled in 1921 and 1923, respectively. Gainesville and Valley View in Cooke County had wells in production in 1912. By 1940, most of the larger towns in Cooke and western Grayson County were obtaining water from the Antlers.

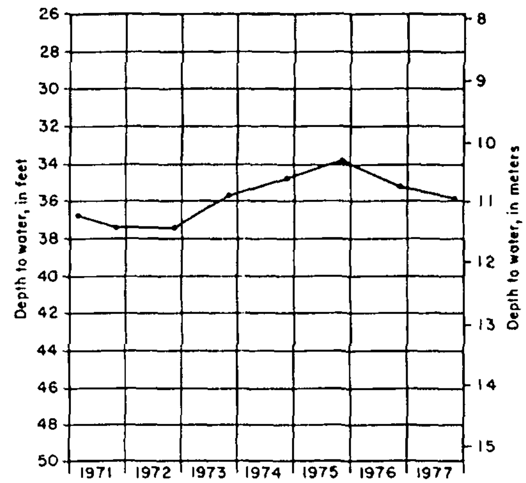
Grayson County is the largest user of public supply water from the Antlers aquifer, pumping 4,627 acre-feet (5.71 hm^3) of water in 1976. Cooke County is second with a total use of 2,803 acre-feet (3.46 hm^3). The city of Sherman used 3,735 acre-feet (4.61 hm^3) in 1976 which is 45 percent of the total amount of ground water pumped from the Antlers for public-supply purposes. The city of Gainesville is the second largest individual user with a total of 1,916 acre-feet (2.36 hm^3) pumped in 1976. These two cities accounted for over 68 percent of the water pumped for public supply use from the Antlers in 1976.

Only 29 industrial wells were located and many are no longer in use. Many industries purchase their water from municipalities. In 1976, ground water pumped from the Antlers for industrial use amounted to only 287 acre-feet (0.354 hm^3). Table 6 shows the amount of industrial pumpage from 1955 to 1976, by county. The largest amount used in a year was 845 acre-feet (1.04 hm^3) pumped in 1959. Wise County had the most pumpage in 1976 with 144 acre-feet (0.188 hm^3), all attributed to one industry. Cooke County produced 113 acre-feet (0.139 hm^3) for industrial purposes in 1976.

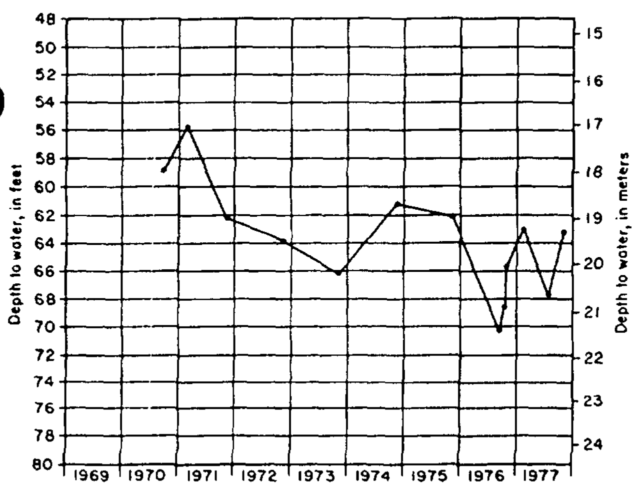
Irrigation is mostly confined to wells located on the Antlers outcrop in Wise, Montague, and Cooke Counties. Only 28 irrigation wells were inventoried, and



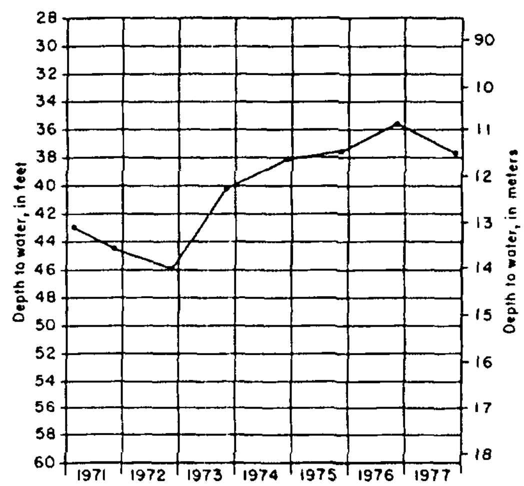
Hood County
Well LY-31-32-901
depth: 46 ft. (14 m)
Twin Mountains Formation



Montague County
Well TR-19-20-201
depth: 128 ft. (39 m)
Antlers Formation



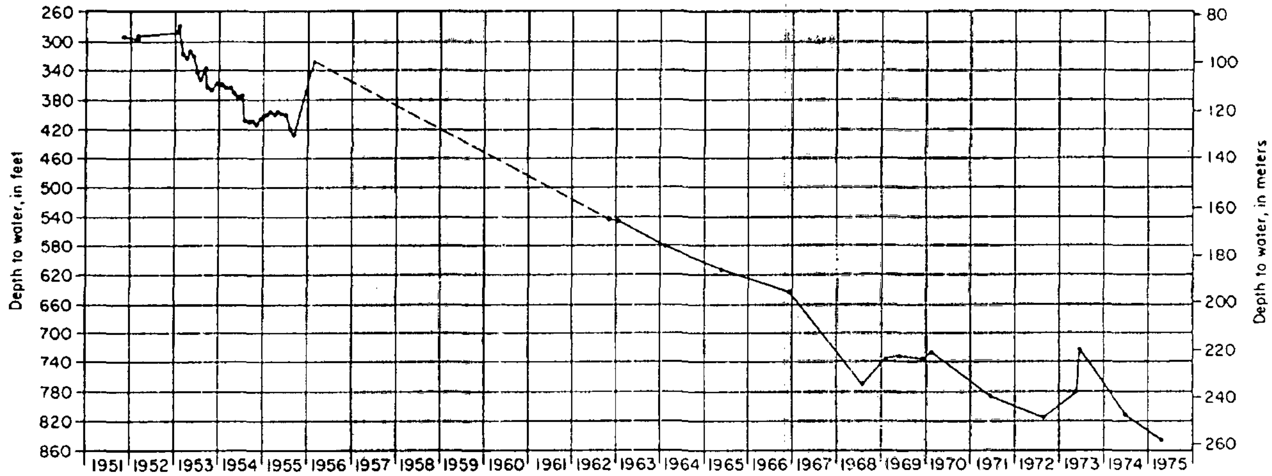
Parker County
Well UP-32-18-201
depth: 96 ft. (29 m)
Paluxy Formation



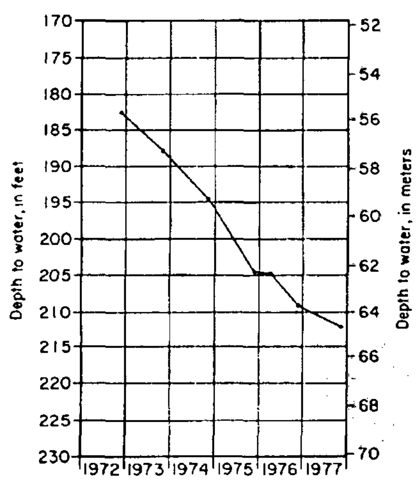
Denton County
Well HW-18-41-201
depth: 210 ft. (64 m)
Woodbine Group

Figure 7

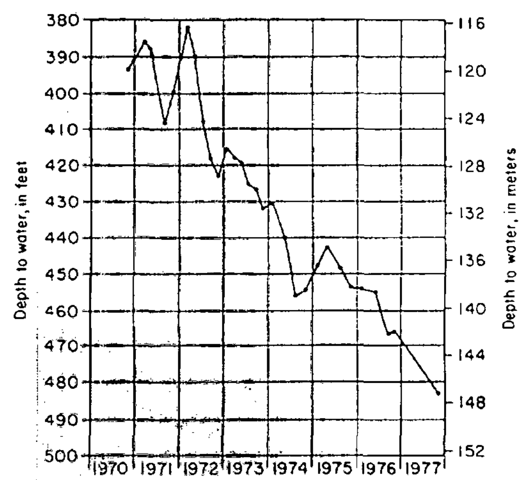
Hydrographs of Water Levels Under Water-Table Conditions



Tarrant County
Well XU-32-15-601
depth: 1,483 ft. (452m)
Twin Mountains Formation



Grayson County
Well KT-18-33-301
depth: 923 ft. (281m)
Antlers Formation



Dallas County
Well HR-33-19-101
depth: 3,076 ft. (938m)
Twin Mountains Formation

Figure 8
Hydrographs of Water Levels in Wells Completed in the Antlers and Twin Mountains Formations Under Artesian Conditions

Table 5.-Estimated Use of Ground Water for Irrigation, 1970-77

Includes irrigation of commercial landscapes as well as crops. Amounts are in acre-feet.
Water-bearing units: Kgw, Woodbine Group; Kcpa, Paluxy Formation; Kctm, Twin Mountains Formation; Kca, Antlers Formation

County	Aaulfer	1970	1971	1972	1973	1974	1975	1976	1977
Cooke	Kgw	88	88	88	88	88	88	221	234
	Kca	175	215	275	279	279	279	278	242
Dallas	Kgw	40	40	40	188	228	285	293	347
	Kcpa	23	23	23	23	23	23	70	89
	Kctrn	285	278	350	353	270	124	371	435
Denton	Kgw	255	255	473	506	566	546	554	50.
	Kctrn	0	150	212	212	341	357	708	762
Grayson	Kgw	890	1,000	1,281	1,313	1,313	1,012	1,158	1,225
Hood	Kctrn	0	57	75	200	200	223	223	199
Johnson	Kgw	0	41	41	41	41	41	41	41
	Kcpa	55	83	83	83	83	83	83	83
Parker	Kcpa	0	0	3	3	3	3	3	3
	KCirl.	0	20	26	28	36	28	30	34
Tarrant	Kgw	83	83	83	129	314	314	340	363
	Kcpa	258	258	275	294	163	163	163	186
	Kctm	99	99	99	99	99	99	99	99
Wise	Kca	8	19	120	135	135	135	45	76
	Kctm		—	—	—	—	—	16	16
Totals	Kgw	1,356	1,507	2,006	2,265	2,550	2,286	2,607	2.717
	Kcpa	336	364	384	403	272	272	319	361
	Kctm	384	604	762	892	946	831	1,447	1,545
	Kca	183	234	395	414	414	414	323	318
		2,259	2,709	3,547	3,974	4,182	3,803	4,696	4,941

production in 1977 accounted for 318 acre-feet (0.392 hm^3). Most of the wells are of small capacity, and there is currently no extensive ground-water irrigation pumpage from the Antlers. The estimates of pumpage are based on power and yield tests and the results of these tests are given in Table 7.

The water provided by the Antlers in the north-northwest part of the study area is excellent for most purposes. Ground water derived from the outcrop is mostly hard to very hard, while water from downdip locations is generally soft. Approximately one-third of the analyses taken had over 60 mg/l hardness as calcium carbonate, with many analyses in Montague and northern Wise Counties containing over 300 mg/l. High iron concentrations near the outcrop are also encountered, with 27 samples exceeding the 0.3 mg/l limit. Of the more than 280 water samples taken from the Antlers, only 26 had dissolved-solids concentrations over 1,000 mg/l and none had more than 2,000 mg/l. Less than 5 percent of the samples contained excess amounts of chloride and sulfate. Two dozen analyses contained fluoride concentrations exceeding the 1.6 mg/l acceptable level for this area. Results of chemical analyses on water from irrigation wells completed in the outcrop showed very low sodium hazard but medium to high salinity hazard. Residual sodium carbonate for all samples was zero. Table 8 shows the range of constituents in ground water from selected wells in the Antlers Formation.

Recharge to the Antlers also occurs on the outcrop in Oklahoma, and well records in northern Grayson County indicate that the Trinity is also being recharged by Lake Texoma. Static and pumping levels in Grayson County are still well above the top of the formation, but higher lifting costs from deeper pumping levels will probably be the limiting factor in development here.

Development of the Antlers in Cooke County is only in the lower section of the aquifer, and although both static and pumping levels are below the top of the upper section, or Paluxy equivalent, the levels are still well above the top of the lower section, or Twin Mountains equivalent. Based on this and pumping levels that are hundreds of feet above the screened intervals, the Antlers is in no immediate danger of being dewatered.

Table 6.--Estimated Use of Ground Water for Public Supply and Industrial Purposes From the Antlers Formation, 1955-76

Use: PS, public supply; Ind, industrial. Values are in acre-feet.

County	Use	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
Cooke	PS	2,649.2	2,682.4	2,289.4	2,073.7	2,052.7	1,896.8	2,019.8	2,770.9	2,732.3	2,124.6	1,859.5
	Ind	422.8	422.8	422.8	202.9	656.0	144.4	154.0	152.3	108.2	78.7	55.3
Denton	PS	191.6	240.0	254.6	220.2	226.8	235.9	231.6	243.9	293.7	271.2	260.3
Grayson	PS	1,647.8	2,050.8	1,890.1	1,812.0	1,848.1	1,859.1	1,928.8	2,137.0	2,646.7	2,626.4	2,687.4
	Ind	18.0	18.0	18.0	54.4	55.0	36.5	36.5	43.2	62.1	77.9	72.2
Montague	PS	114.2	153.1	89.1	69.1	83.8	87.0	95.9	95.8	116.8	109.8	108.5
Wise	PS	316.8	343.7	405.1	364.6	331.2	367.3	312.7	432.9	528.8	475.4	460.0
	Ind	94.8	96.8	96.8	164.2	134.4	171.0	168.3	165.4	76.5	154.1	153.9
Totals	PS	4,919.6	5,470.0	4,928.5	4,539.5	4,542.6	4,456.2	4,588.8	5,680.5	6,318.3	5,607.2	5,375.7
	Ind	537.6	537.6	537.6	421.5	845.4	351.9	358.8	360.9	246.8	310.7	281.4
	PS and Ind	5,457.2	6,007.6	[illegible]	[illegible]	[illegible]	[illegible]	4,967.6	6,041.4	6,565.1	5,917.9	5,657.1

County	Use	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	Totals
Cooke	PS	2,051.6	2,107.3	2,061.9	2,497.8	2,909.6	2,929.3	3,373.3	2,932.1	2,866.3	2,650.4	2,802.8	54,351.7
	Ind	55.4	55.7	45.6	45.2	66.3	146.6	152.8	152.1	106.2	131.2	112.6	3,889.9
Denton	PS	279.5	329.3	312.8	339.0	386.2	405.8	457.1	431.3	514.0	526.2	619.2	7,270.3
Grayson	PS	2,661.4	2,728.7	2,934.1	3,461.4	3,832.3	4,352.5	4,504.0	4,488.0	4,544.6	4,221.2	4,627.1	65,499.3
	Ind	73.8	73.8	73.9	73.9	73.5	51.7	61.2	58.1	67.6	32.1	31.1	1,162.5
Montague	PS	111.0	120.2	125.3	133.2	138.5	134.7	152.4	141.9	143.6	132.3	145.4	2,601.6
Wise	PS	322.0	114.5	67.5	107.7	108.8	64.2	65.7	63.9	64.9	66.6	65.3	5,449.6
	Ind	153.9	153.3	152.4	152.4	153.0	152.7	137.5	132.6	116.2	117.9	143.6	3,043.9
Totals	PS	5,425.5	5,400.0	5,501.6	6,539.1	7,375.4	7,886.5	6,552.5	8,077.2	8,131.4	7,596.7	8,259.8	135,172.5
	Ind	283.1	283.0	271.9	271.5	292.8	351.0	351.5	342.8	290.0	281.2	287.3	8,096.3
	PS and Ind	5,708.6	5,683.0	5,773.5	6,810.6	7,668.2	8,237.5	6,904.0	8,420.0	8,421.4	7,877.9	8,547.1	143,268.8

Table 7.--Power-Yield Tests From Selected Irrigation Wells

Method of Distribution: OD, irrigation well pumping into earthen or concrete tank; D, irrigation well pumping directly to the field through sprinkler lines; OD-EB, irrigation well pumping into earthen or concrete tank, and an electric booster pumping water from the tank to the field through sprinkler lines.

Test Number	Well	Date of Test	Method of distri-bution	Length of Test: Hours	Length of Test: Minutes	Pump Horsepower: Well	Pump Horsepower: Booster	Yield in gal/min: Well	Yield in gal/min: Sprinkler	Total kwh used	Gals/kwh	Kwh/hr	Remarks
Dallas County													
1	HR-33-02-203	Sept. 7, 1976	OD	4	00	125	--	470	--	--	--	--	
2	303	do	OD	4	00	20	--	85	--	96	213	24	
Denton County													
3	HW-18-41-501	Aug. 12, 1976	D	7	00	20	--	--	185	120	648	17.1	
4	19-55-606	Oct. 8, 1976	OD	31	20	20	--	107	--	280	720	8.9	
	606	Aug. 4, 1976	OD	21	10	20	--	105	--	148	910	6.9	
Grayson County													
5	KT-18-17-601	Aug. 11, 1976	OD	3	00	15	--	182	--	41	799	13.7	
6	18-407	Aug. 10, 1976	D	2	20	5	--	55	--	12.2	632	5.2	
7	408	do	D	2	00	10	--	80	--	17.1	842	8.6	
8	409	do	D	1	45	3	--	45	--	4.8	985	2.8	
9	410	do	D	17	25	1.5	--	35	--	29.6	1,236	1.7	
10	412	Aug. 11, 1976	D	4	00	3	--	32	--	13	591	3.3	
11	413	do	D	4	00	3	--	80	--	15.7	1,223	3.9	
12	414	do	OD	4	00	.5	--	8.5	--	4.1	498	1.0	
13	415	Aug. 10, 1976	D	17	35	2	--	60	--	45.2	1,400	2.6	
14	701	Aug. 11, 1976	OD	2	30	20	--	230	--	45.1	765	18	
15	25-606	Aug. 12, 1976	D	2	00	25	--	--	195	45.7	512	22.8	
16	610	Sept. 15, 1976	D	3	00	20	--	--	175	58.2	541	19.4	
17	33-501	Aug. 6, 1976	D	2	12	40	--	--	301	83	478	37.8	
18	602	Aug. 17, 1976	D	0	56	25	--	--	218	26	470	28	
Hood County													
19	LY-32-26-902	Aug. 23, 1976	OD	4	00	30	--	300	--	100	720	25	
20	903	do	OD	3	45	30	--	170	--	100	383	26.7	
21	27-703	do	OD-EB	4	00	30	50	150	--	270	133	67.5	
22	34-112	Aug. 24, 1976	OD	3	20	10	--	145	--	35	829	10.5	
Parker County													
23	UP-32-17-512	July 21, 1976	OD	0	30	5	--	105	--	1.5	2,100	3	
24	516	do	OD	0	22	5	--	105	--	2	1,155	5.4	
Tarrant County													
25	XU-32-07-907	Oct. 19, 1977	OD	2	42	5	--	48	--	36	572	13.3	Three wells pump into earthen tank. All on one meter.
	908					3		40					
	913					5		40					
26	15-903	Sept. 14, 1976	OD	2	30	5	--	20	--	17	177	6.8	
27	904	do	OD	2	30	5	--	20	--	13	232	5.2	
28	22-607	Sept. 15, 1976	OD	3	06	20	--	108	--	52.8	385	16.9	
29	23-607	do	OD	2	30	3	--	39	--	10	578	4	
30	608	do	OD	2	30	3	--	56	--	9	927	3.6	
Wise County													
31	ZR-19-34-703	Aug. 26, 1976	D	3	00	10	--	--	95	86.6	200	28.9	Three wells on three meters pumping through one sprinkler line.
	33-901					15							
	902					5							
32	34-701	do	D	3	30	3	--	--	80	39.1	430	11.2	Five wells on three meters pumping through one sprinkler line.
	702					3							
	42-101					5							
	102					1							
	103					1							

Table 8.--Range of Constituents in Ground Water From Selected Wells in the Antlers Formation

Analyses given are in milligrams per liter except percent sodium, specific conductance, pH, SAR, and RSC.

Single values appear where only one analysis or value was available.

Constituent or property	Montague County	Cooke County	Grayson County	Denton County	Wise County
Silica (SiO_2)	5 - 32	8 - 57	3 - 72	11 - 18	10 - 40
Iron (Fe)	.2- 15	0 - 1.7	0 - 58.5	0 - .1	--
Calcium (Ca)	19 - 256	1 - 127	1 - 253	0 - 7	3 - 235
Magnesium (Mg)	5 - 82	0 - 15	0 - 39	0 - 8	1 - 142
Sodium (Na)	13 - 200	10 - 432	9 - 580	181 - 310	7 - 149
Bicarbonate (HCO_3)	54 - 504	315 - 700	151 - 790	234 - 502	142 - 540
Sulfate (SO_4)	21 - 304	19 - 130	11 - 600	46 - 108	10 - 419
Chloride (Cl)	7 - 434	2 - 484	8 - 590	10 - 67	5 - 394
Fluoride (F)	.1- 1.2	0 - 2.8	.1- 4.2	.1- 1.5	.1- .9
Nitrate (NO_3)	0 - 90	0 - 7.0	0 - 3.7	0 - 4.0	0 - 30
Boron (B)	.1	.3- 1.3	0 - 1.2	--	.1
Dissolved solids	358 -1,238	221 -1,202	269 -1,870	335 - 602	201 -1,587
Total hardness ($CaCO_3$)	20 - 930	1 - 374	1 - 770	1 - 43	7 -1,160
Percent sodium (%)	6.7- 93.7	5.5- 99.5	5.8- 99.6	92.5- 100	5.2- 96.5
pH	6.8- 8.7	7.2- 9.4	6.1- 9.1	8.1- 9.3	6.9- 8.6
Sodium-adsorption ratio (SAR)	.2- 16	.2- 60	.2- 98.1	14.5- 69.7	.1- 19.0
Residual sodium carbonate (RSC)	0 - 6.7	0 - 11.2	0 - 13.8	3.3- 8.2	0 - 5
Specific conductance (micromhos at 25°C)	599 -2,110	594 -2,080	448 -2,646	720 -1,030	338 -2,300

As previously stated, the water table is declining by as much as 7 feet (2 m) per year, reflecting the fact that more water is removed annually from the Antlers than is recharged. With the large saturated sand thicknesses available and proper use of well construction and spacing, no problems seem likely in the immediate future as far as Antlers ground-water availability is concerned.

According to Baker (1960, p. 65), the amount of fresh-water sand decreases northward in Grayson County, chiefly as a result of increasing amounts of salt water in the northern part of the county. The lower part of the Antlers contains saline water in the vicinity of the Preston anticline; therefore, the upper part of the Antlers or the Woodbine should be developed for ground water in this area.

Twin Mountains Formation

The Twin Mountains provides moderate to large quantities of fresh to slightly saline water to wells in nine of the twenty counties included in this study. The outcrop covers approximately 370 square miles (958 km^2) and lies within Hood, Parker, and Wise Counties. As illustrated on the geologic map (Figure 16), this basal Cretaceous aquifer forms the western boundary of this study. Data on the Twin Mountains were obtained prirnarily through the inventory of over 600 public supply, industrial, and irrigation wells located in the study area.

The primary source of ground water in the Twin Mountains is precipitation falling on the outcrop. Other minor sources include surface-water seepage from ponds, lakes, and streams cutting the outcrop. The average annual precipitat ion is about 30 inches (76cm). However, probably less than 1 inch (2.5cm) per year is available for recharge.

Ground water in the Twin Mountains usually occurs under water-table conditions in or near the outcrop, while ground water downdip from the outcrop is under artesian conditions. The lower sands and shales of the Twin Mountains are the hydrologic equivalent of the basal portion of the Antlers. Water-level maps for the Antlers and the Twin Mountains Formations have been combined and are shown on Figures 24, 25 and 28.

The average rate of movement of water in the Twin Mountains is estimated to be less than 2 feet (1m) per year. Ground water moves slowly downdip in an easterly direction except for local changes. Water-level measurements indicate the present hydraulic gradient is extremely variable due to the large cone of depression surrounding the Dallas-Fort Worth metroplex, but in areas beyond this influence, a gradient of approximately 22 feet per mile (4.2 m/km) is average. Altitudes of water levels about 1955 and about 1976 are shown on Figures 24 and 25.

Water is discharged naturally from the Twin Mountains by springs and evapotranspiration and artificially by pumpage. In 1976, over 40,000 acre-feet (49.3 hm^3) of ground water was pumped from the Twin Mountains in the study area.

The coefficients of transmissibility, permeability, and storage for the Twin Mountains Formation are shown in Table 4. This table was compiled from existing literature and from data supplied by well drillers. Transmissibility and permeability values are also represented graphically on Figure 26. Permeability coefficients were computed by dividing the transmissibility of the well by its screened interval. Aquifer test results on 58 Twin Mountains wells were analvzed.

Review of the test results, illustrated on Figure 26, show that transmissibility values are generally higher in the central, northern, and eastern sections of the study area. The range of transmissibility was 1,950 to 29,700 (gal/d)/ft, or 24,200 to 369,000 (l/d)/m. The average for tests in Dallas County was 12,700 (gal/d)/ft, or 158,100 (l/d)/m; tests in Tarrant County was 8,450 (gal/d)/ft, or 105,000 (l/d)/m; and tests in the Johnson-Ellis County area was 6,480 (gal/d)/ft, or 80,500 (l/d)/m. Permeability values ranged from 8 to 165 $(gal/d)/ft^2$, or 326 to 6,720 $(l/d)/m^2$, with an average value of 68 $(Ngal/d)/ft^2$, or 2,770 $(l/d)/m^2$. Storage coefficients were obtained from 14 tests and ranged from 5 X 10^{-4} to 4 X 10^{-5} with an average value of 1 X 10^{-4}, or 0.0001. The specific yield in the outcrop is on the order of 15 percent as estimated by seismic methods (Duffin and Elder. 1979).

Yields of wells completed in the Twin Mountains range from 10 to 1,940 gallons per minute (gal/min) (0.63 to 122 l/s), with an average yield of 286 gal/min (18 l/s) for the 525 wells measured. Yields were considerably lower on or near the outcrop than yields of wells further downdip. Well yields generally increase from the southern part of the study area to the northern part. Both Collin and Dallas Counties have average well yields in excess of 700 gal/min, (44 l/s), while Hood, Parker, and Wise Counties average less than 100 gal/min (6.3 l/s). Denton, Ellis, and Tarrant Counties each average about 300 gal/min (19 l/s). Since many of the wells measured were of small capacity, improperly developed, or did not penetrate the full thickness of the aquifer, well yields are probably greater than the stated averages.

Specific capacities of 233 wells screened in the Twin Mountains range from 0.3 to 12.2 or 0.06 to 2.53 (l/s)/m, and averaged 3.3 (gal/min)/ft, or 0.68 (l/s)/m. Specific capacities are generally higher in the northern and eastern parts of the study area.

Wells completed in the Twin Mountains outcrop have not experienced water-level declines other than the normal seasonal fluctuations. Water levels in wells east of the outcrop are declining steadily. The changes in water levels are illustrated on Figure 28 and by hydrographs (Figures 7 and 8). Long-range declines average over 20 feet (6 m) per year in eastern Tarrant and western Dallas Counties, corresponding to the center of the cone of depression as illustrated by the water-level maps (Figures 24 and 25). In areas outside this influence, water levels are declining 9 (3 m) to 17 (5 m) feet annually.

The large cone of depression depicted on Figure 25 is centered in the area between Euless in Tarrant County and Grand Prairie in Dallas County. Static water levels in several wells have reached the 1,000 foot (305 m) level and pumps are set as low as 1,500 feet (457 m) below the land surface. Yields have diminished and pumping-lift costs have risen. Lowering of pumps is a common occurrence. Several large ground-water users in this area, namely Euless, Bedford, and Arlington, have changed to surface-water supplies. This resultant decrease in pumpage may help alleviate the water-level declines now being experienced.

Wells which are not in the immediate vicinity of the cone of depression have also experienced large annual declines. A well at Everman in Tarrant County, had a water-level decline of 530 feet (162 m) over a 26-year period. The level in a well at Lancaster in Dallas County, declined 362 feet (110 m) in a 23-year period, and at Flower Mound in Denton County, a decline of 160 feet (49 m) in less than 9 years has occurred. Water-level declines are commonplace and are about average over most of the study area.

About half the ground water from the Woodbine and Trinity Group aquifers, over 40,000 acre-feet (49.3 hm^3), was pumped from the Twin Mountains in 1976. Public-supply use accounted for over 31,000 acre-feet (38.2 hm^3), more than the total public-supply use for all other aquifers in the study area combined. Almost all municipal, industrial, and irrigation wells were inventoried for this study. Data on 613 wells were tabulated and compiled within the record of wells. In areas where no large capacity wells exist, livestock or domesr'c wells were inventoried to provide more complete coverage. The estimated amount of ground water pumped from the Twin Mountains is shown in Tables 5 and 9. Domestic wells pumped an estimated 1,200 acre-feet (1.48 hm^3) of water from the Twin Mountains in 1975.

Public-supply wells accounted for 31,120 acre-feet (38.4 hm^3) of water from the Twin Mountains in 1976. This amount is double the quantity pumped in 1960. The greatest amount pumped during a single year was 32,468 acre-feet (40.0 hm^3) in 1974. Over the years, Dallas County pumpage has steadily increased, with almost 18,000 acre-feet (22.2 hm^3) pumped in 1976. Tarrant County increased each year until 1972, when Arlington, Bedford, and Euless changed to surface water. The amount of ground water pumped from the Twin Mountains in Tarrant County declined from 12,688 acre-feet (15.6 hm^3) in 1972 to only 6,080 acre-feet (7.50 hm^3) in 1976. Table 9 shows the public supply and industrial pumpage from 1955 to 1976.

Data were collected on 437 public-supply wells completed in the Twin Mountains. Of this amount, 105 are located in Tarrant County. Dallas, Denton, and Hood Counties average 70 wells each. Many of the wells inventoried in Tarrant and Dallas Counties have been abandoned. The largest individual user of ground water is Grand Prairie, pumping approximately 6,706 acre-feet (8.26 hm^3) in 1976. The four largest users are all in Dallas County, including Grand Prairie, Irving (4,812 acre-feet) (5.93 hm^3), Carrollton (2,080 acre-feet) (2.56 hm^3), and Lancaster (l ,348 acre-feet) (1.66 hm^3). These four cities had a 1976 total pumpage of almost 15,000 acre-feet (18.5 hm^3), which is about half of all the ground water pumped from the Twin Mountains for public-supply purposes in the study area. Grand Prairie and Irving are both situated near the center of the cone of depression previously mentioned. When Arlington, Bedford, and Euless were operating wells, an additional 5,000 acre-feet (6.17 hm^3) of ground water was also pumped from near the center of the cone.

Use of ground water for industrial purposes has diminished over the last 12 years. As shown in Table 9, approximately 6,000 acre-feet (7.40 hm^3) was pumped in 1976, just about one-half the amount, used in 1964. The inventory of wells resulted in the location of 113 industrial wells in the study area, many of which are now abandoned. About 70 percent of the industrial wells inventoried are located in Dallas and Tarrant Counties.

Ground-water irrigation constitutes only a small portion of the pumpage from the Twin Mountains. According to Table 5, approximately 1,545 acre-feet (1.90 hm^3) was pumped for irrigation purposes in 1977. Most of the water was used to irrigate golf courses and lawns. Irrigation of crops is limited to the outcrop area

Table 9.—Estimated Use of Ground Water for Public Supply and Industrial Purposes From the Twin Mountains Formation, 1955-76

Use: PS, public supply, Ind, industrial. Values are in acre-feet.

County	Use	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
Collin	PS	1,205.9	1,012.8	326.9	309.1	302.6	22.1	24.6	24.6	30.9	64.4	65.1
	Ind	1,739.8	1,723.2	1,707.8	1,525.9	1,079.3	1,774.5	1,646.1	2,019.8	1,852.4	2,489.0	2,019.9
Dallas	PS	10,481.6	10,573.2	7,451.8	7,918.5	7,888.6	6,403.5	7,232.6	7,323.5	7,882.5	8,239.2	8,126.3
	Ind	6,434.6	6,414.6	[illegible]	4,929.3	5,633.5	5,075.2	[illegible]	5,450.1	6,230.3	5,696.6	5,606.3
Denton	PS	3,271.5	3,747.5	3,952.8	674.1	381.0	374.8	418.6	505.4	618.2	609.8	566.3
Ellis	PS	1,386.9	1,586.6	1,041.8	1,172.9	1,005.3	162.7	199.0	177.3	194.3	302.2	214.9
	Ind	--	--	--	--	--	220.0	220.0	220.0	220.0	220.0	270.0
Hood	PS	111.6	196.0	236.4	263.4	346.0	367.2	367.1	399.2	410.3	447.0	415.2
	Ind	--	--	--	--	--	--	--	--	--	--	--
Johnson	PS	2,211.0	2,580.0	2,307.6	1,937.1	2,452.9	2,144.3	1,566.2	2,632.7	2,533.4	2,413.2	1,221.6
	Ind	--	--	--	--	--	76.1	260.9	260.9	260.9	182.3	182.3
Parker	PS	808.3	910.8	572.6	17.0	15.0	16.0	51.0	50.9	66.5	68.2	262.7
	Ind	161.3	161.3	161.3	165.2	80.9	161.3	177.6	166.0	166.0	166.0	268.0
Tarrant	PS	6,193.8	6,191.6	6,866.5	5,927.6	6,217.2	6,026.4	5,710.2	6,112.2	7,826.4	8,001.7	9,881.0
	Ind	3,654.7	3,654.7	3,654.7	3,597.9	2,773.3	2,546.9	2,532.3	2,894.1	2,904.9	3,150.0	2,971.6
Wise	PS	90.3	90.3	90.3	[illegible]	37.0	34.4	32.6	29.1	29.1	44.6	23.6
	Ind	--	--	--	--	--	--	--	--	--	--	--
Totals	PS	25,759.6	26,903.9	22,924.6	18,313.8	18,644.9	15,271.4	16,604.4	17,256.9	19,578.3	20,190.3	20,774.9
	Ind	11,970.4	11,951.8	11,938.4	10,197.3	5,569.0	9,804.0	9,948.4	11,012.9	11,636.5	12,108.1	11,220.1
	PS and Ind	37,779.0	38,857.6	34,763.0	28,511.1	24,213.9	25,075.4	26,552.8	28,267.8	31,215.2	32,298.4	31,995.0

County	Use	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	Totals
Collin	PS	64.3	102.7	106.7	120.6	127.8	134.4	171.5	177.2	205.8	185.3	193.2	4,976.1
	Ind	1,967.1	1,821.2	1,730.8	1,966.8	2,256.6	2,241.8	2,012.5	1,808.0	770.0	339.0	451.0	37,088.7
Dallas	PS	8,875.7	9,391.0	8,755.5	9,440.7	10,095.1	9,451.4	11,104.4	11,817.4	13,263.8	15,569.2	17,869.2	214,837.1
	Ind	5,774.0	5,626.7	4,441.3	5,002.0	4,585.9	4,055.4	4,792.3	3,907.6	4,441.6	2,309.0	2,232.5	110,348.3
Denton	PS	718.6	923.3	1,081.2	1,325.5	1,576.9	1,846.6	2,550.3	2,434.5	3,168.5	2,237.1	1,389.4	33,990.9
Ellis	PS	329.8	458.6	411.0	793.1	856.6	1,014.7	1,266.8	1,184.1	1,409.9	1,463.5	1,490.0	18,121.9
	Ind	420.0	420.0	445.0	462.5	638.5	788.1	868.4	1,952.7	1,047.8	1,013.5	1,011.9	9,533.2
Hood	PS	373.1	364.2	343.6	407.4	479.2	601.0	759.4	773.9	[illegible]	[illegible]	[illegible]	[illegible]
	Ind	--	--	--	--	--	--	--	--	--	41.5	43.2	84.7
Johnson	PS	626.7	942.5	993.9	1,350.8	1,444.4	1,583.0	1,955.0	1,406.2	2,487.5	2,397.6	2,541.4	43,177.1
	Ind	271.9	271.9	271.9	271.9	271.9	709.4	708.3	709.3	797.7	698.0	767.6	6,952.4
Parker	PS	247.3	262.8	280.7	332.1	369.8	472.4	488.2	543.2	428.1	493.5	358.7	7,454.9
	Ind	168.0	168.0	159.0	197.2	296.9	240.6	219.4	18.4	18.4	6.1	4.3	3,344.1
Tarrant	PS	9,366.6	10,850.1	10,926.3	12,256.2	11,298.7	10,991.2	12,668.3	10,623.4	10,492.0	6,591.0	6,079.5	186,995.2
	Ind	3,006.0	2,962.1	3,079.1	2,915.9	2,697.4	1,593.6	1,310.6	1,742.2	1,336.6	1,512.1	1,415.1	58,105.8
Wise	PS	22.3	40.2	36.2	22.9	22.9	68.2	86.5	76.0	81.9	75.5	87.8	1,198.5
	Ind	--	--	--	--	--	--	--	64.3	80.7	161.3	80.7	387.0
Totals	PS	20,626.4	23,339.4	22,937.4	26,047.3	26,255.6	26,062.9	31,081.7	29,333.9	32,467.9	30,003.4	31,120.1	521,436.7
	Ind	11,607.2	11,269.9	10,327.1	10,808.3	10,690.5	9,629.1	9,911.5	9,301.5	8,685.8	6,078.3	5,986.3	225,644.2
	PS and Ind	32,233.6	34,609.3	33,264.5	36,855.6	36,946.1	35,692.0	40,993.2	38,635.4	41,153.7	36,081.7	37,106.4	747,080.9

in Hood, Parker, and Wise Counties. Forty-seven irrigation wells that were inventoried accounted for 16 percent of the 1977 pumpage from the Twin Mountains.

The Twin Mountains Formation is the most prolific of the Cretaceous aquifers in the study area with about 55 percent of the total quantity of ground water utilized for municipal and industrial purposes. The quality of water is generally not as good as from the Paluxy or Antlers. However, higher well-yields allow some sacrifice in chemical quality. Approximately 700 analyses of water samples from the Twin Mountains have been tabulated and included in Table 10 which shows the range of constituents and properties of the water from representative wells. About 22 percent of these analyses contained dissolved-solids concentrations in excess of 1,000 mg/l.

Similar to the other Cretaceous aquifers in this study, the ground water from wells drilled on the outcrop of the Twin Mountains is hard and contains high concentrations of dissolved iron. In the downdip area, about 9 percent of the samples contain dissolved iron concentrations in excess of the recommended limit of 0.3 mg/, and about 83 percent of'the water is soft. The maximum allowable level for fluoride in the study area is 1.6 mg/l according to Drinking Water Standards adopted by the Texas Department of Health. Over 230 analyses contained fluoride levels exceeding 1.6 mg/l. Most of the other constituent levels were close to the maximum. Therefore, the main problems related to water quality for this aquifer are excessive fluoride and dissolved-solids concentrations. The downdip limit of fresh to slightly saline water is encountered about 60 to 75 miles (97 to 121 km) east-southeast of the outcrop in the majority of the study area (Figure 25). This distance is considerably less in the northern part of the study area where the outcrop trends eastward in the vicinity of Red River.

Since there are no concentrated areas of ground-water irrigation on the Twin Mountains outcrop, not enough chemical-quality data could be obtained to present a detailed classification of irrigation waters. Generally speaking, the Twin Mountains irrigation wells that are scattered through northeastern Hood County showed a very high sodium hazard, medium to high salinity hazard, and RSC levels classified as unsuitable for irrigation. Limited use of these wells accompanied with crop rotation and good management is necessary for continued good land productivity.

Irrigation wells, located near Brock in Parker County and completed on the Twin Mountains outcrop, were sampled and the results showed a low sodium hazard, medium salinity hazard, and zero RSC. The quality of water from 30 wells was suitable for irrigation use, but well yields limited extensive development.

Figure 29 shows the net sand thickness of fresh to slightly saline water-bearing sand in the Twin Mountains. Net sand thickness generally increases downdip in an easterly direction. Thickness increases from less than 100 feet (30 m) near the outcrop to over 400 feet (122 m) near the downdip limit of fresh to slightly saline water.

Areas for future development would have to be outside the Dallas-Fort Worth metroplex cone of depression. Even outside this influence, water levels are dropping over 10 feet (3 m) per year. There are several areas where waier quality restricts development of wells for irrigation use as previously noted and depicted on Figure 23. Wells tapping the Twin Mountains aquifer in areas downdip from the outcrop and in areas where quality is not a problem can expect a steady decline in water levels and yields.

Paluxy Formation

The Paluxy yields small to moderate amounts of fresh to slightly saline water to public supply, industrial, domestic and livestock wells in 16 of the 20 counties included in this study. The majority of the Paluxy outcrop occurs in Hood, Parker, Tarrant, and Wise Counties as illustrated on the geologic map (Figure 16) and occupies about 650 square miles (1,684 km^2).

The primary source of recharge to the Paluxy is precipitation on the outcrop. Secondary sources include recharge from streams flowing across the outcrop and surface-water seepage from lakes. The Brazos and Trinity River systems and Eagle Mountain Reservoir are a few examples. The average annual precipitation on the outcrop is about 31 inches (79 cm). Only a small fraction of the amount is available as effective recharge since there is much runoff and evapotranspiration.

Water in the outcrop area is under water-table conditions and water levels remain fairly constant with only normal seasonal fluctuations. In downdip areas, water is under artesian conditions, and is confined under hydrostatic pressure from overlying formations. The average rate of movement of water in the Paluxy amounts to less than 2 feet (0.6 m) per year in an easterly direction except in downdip areas of heavy pumpage where cones of depression have occurred and movement is towards the center of the pumped wells. Water-level measurements indicate that the present hydraulic gradient is approximately 27 feet per mile

Table 10.--Range of Constituents in Ground Water From Selected Wells in the Twin Mountains Formation

Analyses given are in milligrams per liter except percent sodium, specific conductance, pH, SAR, and RSC.

Single values appear where only one analysis or value was available.

Constituent or property	Collin County	Dallas County	Denton County	Ellis County	Hood County	Johnson County	Parker County	Tarrant County	Wise County
Silica (SiO_2)	10 - 21	4 - 40	7 - 38	2 - 79	0 - 102	8 - 28	9 - 48	5 - 79	8 - 27
Iron (Fe)	0 - .8	0 - 9.4	0 - 8.8	.1- .9	0 - 3.6	0 - .4	0 - 17.2	0 - 2.6	.1- 1.3
Calcium (Ca)	3 - 21	0 - 36	0 - 34	2 - 26	1 - 192	1 - 17	1 - 266	1 - 114	1 - 182
Magnesium (Mg)	1 - 4	0 - 56	0 - 11	0 - 25	0 - 35	0 - 8	1 - 79	0 - 11	1 - 82
Sodium (Na)	228 - 620	150 - 666	170 - 760	241 - 532	8 - 283	192 - 305	5 - 442	141 - 670	34 - 600
Bicarbonate (HCO_3)	293 - 538	185 - 640	244 - 680	360 - 646	240 - 590	356 - 483	35 - 700	288 - 659	303 - 550
Sulfate (SO_4)	73 - 504	19 - 940	38 - 335	70 - 500	4 - 339	41 - 251	4 - 519	21 - 579	24 - 263
Chloride (Cl)	28 - 740	36 - 364	10 - 090	67 - 383	3 - 258	13 - 93	7 - 306	14 - 650	8 - 680
Fluoride (F)	.2- 3.6	.2- 16.0	0 - 3.4	1.1- 3.0	.1- 3.2	.1- 2.7	0 - 3.9	0 - 7.0	.1- 1.5
Nitrate (NO_3)	0 - 2.0	0 - 3.9	0 - 5.2	0 - 5.0	0 - 162	0 - 3.0	0 - 170	0 - 5.9	.4- 44.0
Boron (B)	--	.1- 1.0	.3- 1.0	.4- 1.1	.1- .8	.4- .7	.1- 1.0	.2- 1.9	.2- .7
Dissolved solids	590 -1,612	420 -2,002	307 -1,973	554 -1,408	265 -1,366	382 - 844	133 -1,735	38[illegible] -1,735	387 -1,654
Total hardness ($CaCO_3$)	11 - 65	8 - 230	1 - 60	2 - 110	6 - 600	4 - 28	9 - 914	5 - 302	5 - 770
Percent sodium (%)	93.2- 98.5	80.1- 99.2	88.4- 100	77.7- 98.9	6.7- 99.5	87.0- 99.3	8.5- 99.1	12.8- 99.3	18.6- 98.7
pH	8.0- 8.8	7.7- 9.1	7.2- 9.3	7.6- 9.2	6.9- 8.9	7.9- 9.0	7.0- 8.8	7.4- 9.1	6.8- 8.8
Sodium-adsorption ratio (SAR)	21.8- 57.7	5.4- 66.0	11.1- 73.2	9.2- 63.8	.2- 64.1	11.2- 65.0	.2- 56.5	.4- 72	.8- 38.0
Residual sodium carbonate (RSC)	4.3- 7.9	0 - 10.2	2.3- 10.6	2.6- 10.1	0 - 9.3	5.6- 7.7	0 - 11.1	0 - 10.1	0 - 8.5
Specific conductance (micromhos at 25°C)	1,040 -2,790	510 -3,108	610 -4,030	1,000 -2,310	451 -1,960	780 -1,420	201 -2,270	607 -3,317	706 -2,880

(5.1 m/km). Altitudes of water levels about 1955 and about 1976 are shown on Figures 30 and 31.

Discharge from the Paluxy occurs naturally through springs and evapotranspiration and artificially through pumpage from water wells. In 1976, approximately 13,550 acre-feet (16.7 hm^3) was pumped from the Paluxy for municipal, industrial, irrigation, and domestic purposes. Livestock use would probably add several thousand acre-feet (several cubic hectometers) more to this quantity.

Table 4 shows the results of pumping tests conducted in the study area. Test results were obtained from existing literature or from data supplied by well drillers. A total of 25 Paluxy public-supply wells were tested and transmissibilities determined. Permeabilities were determined by dividing the transmissibility of the well by its screened interval. No tests were conducted on the outcrop, under water-table conditions.

Transmissibility values in 25 tests range from 1,263 to 13,808 (gal/d)/ft, or 15,700 to 171,500 (l/d)/m, with an overall average of 3,700 (gal/d)/ft, or 45,900 (l/d)/m. Only three tests exceeded 6,600 (gal/d)/ft, or 82,000 (l/d)/m, while nine tests fell below 3,000 (gal/d)/ft, or 37,300 (l/d)/m. Generally, the net sand thickness increases from less than 50 feet (15 m) in the southwest portion of the study area to 190 feet (58 m) in Denton County. Coefficients of permeability at 25 well locations were highly variable. A range of 6 to 150 (gal/d)/ft^2, or 244 to 6,110 (l/d)/m^2, was encountered with an overall average of 50 (gal/d)/ft^2, or 2,040 (l/d)/m^2. Of the 18 aquifer tests conducted in Tarrant County, two transmissibilities were extremely high and probably not representative. Eliminating the two high results, the average transmissibility for 16 tests is 3,580 (gal/d)ft, or 44,500 (l/d)/m, and the average permeability is 44 (gal/d)/ft^2, or 1,790 (l/d)/m^2. Permeabilities probably increase from the outcrop in a downdip direction and from south to north, corresponding to increasing sand thicknesses. Storage coefficients were determined at five sites, four of which are in Tarrant County. Values range from 0.00002 to 0.00034 with an average of 0.00014. This value is probably applicable to most of the study area. The specific yield in the outcrop is on the order of 15 to 20 percent as estimated by seismic methods (Duffin and Elder, 1979).

Yields of wells completed in the Paluxy ranged from 10 to 482 gal/min (0.63 to 30 l/s). A total of 344 wells were measured with an average yield of 97 gal/min (6.1 l/s). Lower yields were obtained in wells completed on or near the outcrop, while wells in downdip areas had significantly larger yields due mainly to the larger available heads. The following table lists counties that use water from the Paluxy aquifer extensively.

County	Number of Wells Measured	Average Yield (gal/min)	Number of Wells Tested	Average Specific Capacity [(gal/min)/ft]
Collin	9	132	3	2.39
Dallas	37	189	13	2.13
Denton	27	84	12	1.85
Johnson	19	68	6	1.08
Parker	21	45	13	1.35
Tarrant	214	84	95	1.56

Many of the wells do not penetrate the entire aquifer and are not designed for maximum production. Well completion techniques and pump capacities also affect production. Therefore, yields of many wells are somewhat less than the maximum yields that could be developed. Four flowing wells were measured in Red River County near the Red River and had an average yield of 300 gal/min (19 l/s). Several wells in Fannin, Lamar, Kaufman, Rockwall, and Ellis Counties were measured and yields of at least 100 gal/min (6.3 l/s) were obtained. The specific capacities of 152 wells screened in the Paluxy sand ranged from 0.3 to 5.4 (gpl/min)/ft, or 0.06 to 1.1 (l/s)/m, and averaged 1.64 (gal/min)/ft, or 0.34 (l/s)/m. The specific capacities increase toward the east in a downdip direction. Variations over short distances are due mainly to well construction and to lithologic changes.

Changes in water levels of wells completed in the Paluxy aquifer are illustrated by hydrographs (Figures 7 and 9) and a water-level decline map (Figure 32) showing approximate declines in the vicinity of Dallas and Tarrant Counties from about 1955 through about 1976. There are no long-range declines in the outcrop of the Paluxy or adjacent to it. The aquifer is under water-table condtions in this region and observation wells show minor fluctuations from year to year. However, the Lake Worth-White Settlement-Benbrook area of Tarrant County lies adjacent to the outcrop and due to heavy pumpage of the Paluxy, declines of several feet (meters) per year have been observed. Substantial withdrawals of water in the Tarrant County vicinity are reflected in the large cone of depression illustrated on Figure 31. The cone is at its deepest point in the Euless area of Tarrant County where the static water level of the Paluxy declined over 350 feet (107 m) in the last 20 years. The abandonment of Paluxy public-supply wells in this area during recent years should reflect rising water levels in the near future. The steady decline exhibited throughout the study area downdip from the outcrop is a result of the low permeability of the water-bearing sands and the large amount of ground water used for public supply and domestic purposes.

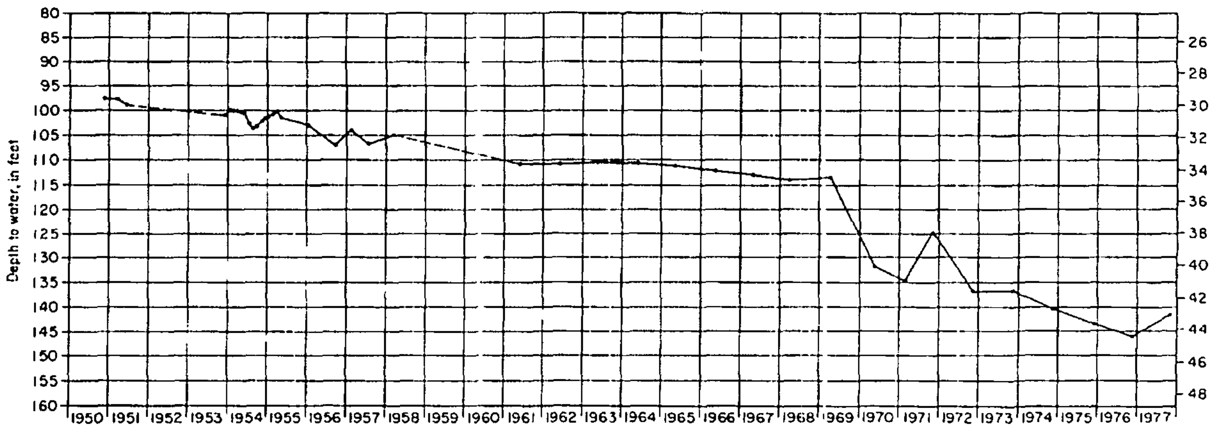
Approximately 15,000 acre-feet (18.5 hm^3) of water was withdrawn from the Paluxy in 1976, which is about 17 percent of the total amount pumped from the Woodbine and Trinity Group aquifers for the year. Municipal pumpage accounted for over half of this amount while domestic use accounted for about 24 percent. An attempt was made to inventory all large-capacity Paluxy wells developed for public supply, industry, and irrigation purposes. Of the 650 wells inventoried, 480 were used for public supply, and of this amount, approximately 40 percent are no longer in use. The estimated amount of ground water pumped from the Paluxy is shown in Tables 5 and 11.

Public-supply wells pumped 8,320 acre-feet (10.3 hm^3) of ground water from the Paluxy in 1976. Development of the Paluxy, especially in Tarrant County, began at the turn of the century and by the 1950's. large quantities of water were being withdrawn. In 1955, Tarrant County used 5,628 acre-feet (6.94 hm^3) for public supply, and Dallas County pumped 1,718 acre-feet (2.12 hm^3). This accounted for 88 percent of the public-supply pumpage from the Paluxy for the year. According to Table 11, Dallas and Tarrant Counties pumped 72 percent of the ground water used for public-supply in 1976. The concentrated pumpage in these two counties has resulted in the large cone of depression located in eastern Tarrant County. Of the 480 Paluxy public-supply wells inventoried, 285 were located in Tarrant County and 105 of these have been abandoned. Many of the cities near the center of the cone of depression have abandoned Paluxy wells due to diminishing well yields and declining water levels. Pumping levels in some wells fall below the top of the screened interval. Dewatering of the aquifer in this area has been taking place for the last 25 years. Municipalities using large amounts of ground water in 1976 include the cities of Benbrook, acre-feet (1.34 hm^3); Grand Prairie, 900 acre-feet (1.11 hm^3); Colleyville, 433 acre-feet (0.533 hm^3); and White Settlement, 420 acre-feet (0.517 hm^3). Domestic pumpage for 1976 is estimated at 3,550 acre-feet (4.38 hm^3).

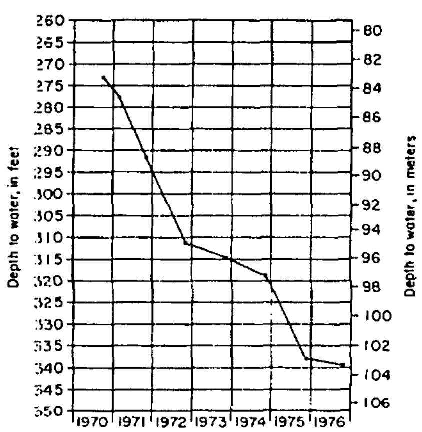
Industrial use accounted for 1,365 acre-feet (1.68 hm^3) in 1976. Of the 126 Paluxy industrial wells inventoried, 80 were located in Tarrant County and pumped 643 acre-feet (0.793 hm^3) in 1976. About one-fourth of these wells are no longer used. Only 18 industrial wells were developed in Dallas County but production in 1976 amounted to 519 acre-feet (0.640 hm^3). The most ground water pumped in any one year for industrial purposes from the Paluxy was in 1973 when 2,035 acre-feet (2.51 hm^3) was withdrawn.

Only minor amounts of water for irrigation purposes are pumped from the Paluxy, with about 361 acre-feet (0.445 hm^3) used in 1977 from 44 wells, Most of these wells are located in Dallas, Parker, Red River, and Tarrant Counties. The wells are widely scattered and are primarily used for watering golf courses and greenbelt areas around industries. Four flowing wells in Red River County were inventoried; one well was flowing in excess of 400 gal/min (25 l/s).

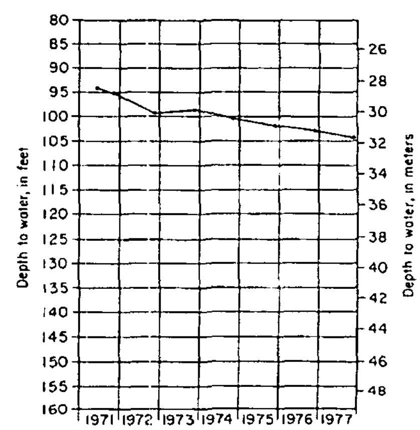
Wells completed in the Paluxy have water with chemical quality that is generally better than water from other Cretaceous aquifers in the study area. Over 600 analyses were collected or obtained from other sources, providing an adequate chemical quality network with the exception of the northeastern area. Most of the minor deficiencies found in Paluxy water exist on or near the outcrop, hardness and higher iron concentrations occur. Approximately 25 percent of the analyses show hardness as $CaCO_3$ exceeding the 60 mg/l level, and many exceed the 120 mg/l and 180 mg/l level. About 40 analyses had iron concentrations in excess of the recommended level of 0.3 mg/l. Only 7 percent of the analyses had more than 1,000 mg/l dissolved-solids and only 9 analyses had concentrations in excess of 2,000 mg/l. Fluoride levels increase in the downdip part of the aquifer, with rnost of the water exceeding 1.6 mg/l near the downdip limit of fresh to slightly saline water. Only a few water wells tap the Paluxy in Fannin, Lamar, and Red River Counties; however, they contain water of good quality. 'Well yields and construction costs limit Paluxy well development in this area. Table 12



Tarrant County
Well XU-32-21-501
depth: 227 ft. (69m



Denton County
Well HW-18-57-901
depth: 1,308 ft. (399m)



Lamar County
Well RT-17-29-601
depth: 2,644 ft. (806m)

Figure 9

Hydrographs of Water Levels in Wells Completed in the Paluxy Formation Under Artesian Conditions

Table 11.--Estimated Use of Ground Water for Public Supply and Industrial Purposes from the Paluxy Formation, 1955-76

Use: PS, public supply; Ind, industrial. Values are in acre-feet.

County	Use	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	Totals
Collin	PS	134.1	156.8	100.0	112.3	96.0	127.7	112.8	114.4	133.9	108.3	109.0	128.0	158.5	132.3	157.6	176.2	186.2	204.1	229.6	264.6	258.5	281.3	3,482.2
	Ind	154.7	154.7	154.7	138.1	150.0	156.5	162.7	159.6	159.6	161.1	165.7	151.4	147.3	7.2	59.0	117.4	107.3	124.8	309.1	242.7	183.1	203.2	3,371.9
Dallas	PS	1,718.3	1,723.3	1,285.7	1,666.6	1,549.9	1,555.2	1,472.5	1,390.4	1,570.8	1,413.5	1,221.0	1,083.7	1,094.7	1,106.7	1,221.4	1,219.8	1,340.9	1,283.3	1,094.6	849.6	1,255.0	1,238.0	29,349.4
	Ind	947.2	947.2	1,100.6	742.0	992.2	898.2	785.3	831.4	765.9	704.0	836.0	849.1	903.7	769.1	786.9	756.5	781.1	1,034.2	971.5	938.4	579.4	518.5	18,438.4
Delta	PS	--	--	--	--	--	--	--	--	--	2.2	12.9	21.5	40.6	51.2	61.7	69.6	71.6	71.6	67.6	81.7	96.3	64.7	713.2
Denton	PS	203.8	193.0	227.6	240.9	275.7	526.3	395.1	353.5	398.7	458.8	489.2	460.9	485.1	573.3	593.2	446.7	476.5	607.1	626.0	747.2	539.9	469.9	9,798.4
	Ind	8.5	9.2	9.2	46.3	50.0	60.0	48.1	55.7	41.5	45.3	45.0	60.3	61.3	56.7	40.1	1.7	2.7	2.8	--	--	--	--	644.4
Ellis	Ind	--	--	--	--	--	--	--	--	--	--	--	--	--	119.0	119.0	119.0	119.0	117.6	156.1	183.2	181.7	175.2	1,290.0
Fannin	PS	--	--	--	--	--	--		--	19.9	46.7	46.7	68.5	76.0	66.9	70.8	76.3	83.0	87.1	100.7	257.9	372.6	345.2	1,717.8
Johnson	PS	348.6	401.8	385.6	389.6	397.5	437.3	520.8	510.9	556.7	469.9	449.8	532.7	401.9	440.4	851.0	572.7	378.5	357.8	340.9	393.7	385.1	473.2	9,995.9
Kaufman	PS	92.1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	92.1
Lamar	PS	--	--	--	--	--	--	--	--	--	--	9.0	29.4	34.7	48.3	63.9	62.3	94.0	104.7	92.0	95.8	131.9	100.5	866.5
Parker	PS	2.5	2.5	2.5	2.5	2.5	3.0	3.0	3.7	3.9	6.3	11.8	27.0	36.4	51.7	76.1	73.5	112.3	138.4	140.1	197.5	213.1	277.3	1,389.4
Red River	PS	--	--	--	--	--	--	--	5.0	25.0	26.0	28.0	30.0	30.0	30.0	33.2	43.5	54.7	55.4	56.2	57.7	58.0	67.8	600.5
Rockwall	PS	143.4	139.7	59.2	8.4	3.3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	354.0
Tarrant	PS	5,627.7	5,631.9	5,804.1	5,795.5	5,916.2	6,349.8	6,880.5	7,763.4	8,945.2	8,050.4	7,887.9	6,831.4	7,214.4	7,050.8	7,891.1	6,871.7	6,135.5	6,346.1	5,608.0	5,197.0	4,789.8	4,724.3	143,312.7
	Ind	720.2	720.2	720.2	825.1	827.2	808.1	802.8	797.1	908.6	791.5	603.0	681.8	888.0	774.3	957.2	745.1	591.1	613.9	733.6	590.7	518.3	642.6	16,280.0
Wise	PS	48.9	32.4	36.7	58.8	61.4	63.4	43.2	37.3	42.2	23.0	24.9	69.6	72.2	74.4	75.2	61.9	79.6	69.0	81.0	96.4	85.3	98.8	1,335.6
	Ind	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	.9	.4	.4	.9	.4	3.0
Totals	PS	8,319.4	8,281.4	7,901.6	8,276.8	8,302.5	9,062.5	9,427.9	10,188.6	11,696.3	10,605.4	10,289.7	9,282.7	9,634.5	9,745.0	11,250.0	9,795.2	9,131.6	9,442.4	8,592.8	8,421.8	8,367.2	8,316.2	204,297.7
	Ind	1,830.6	1,831.3	1,984.7	1,751.5	2,019.4	1,922.8	1,798.9	1,843.8	1,875.6	1,701.9	1,649.7	1,744.6	2,000.3	1,607.3	1,809.4	1,620.7	1,482.2	1,776.6	2,034.6	1,771.6	1,281.7	1,364.7	38,737.7
	PS and Ind	10,150.0	10,112.7	9,886.3	10,028.3	10,371.9	10,985.3	11,226.8	12,032.4	13,571.9	12,307.3	11,939.4	11,027.3	11,634.8	11,352.3	13,059.4	11,415.9	10,613.8	11,219.0	10,627.4	10,193.4	9,648.9	9,680.9	243,035.4

Table 12.--Range of Constituents in Ground Water From Selected Wells in the Paluxy Formation

Analyses given are in milligrams per liter except percent sodium, specific conductance, pH, SAR, and RSC.

Single values appear where only one analyses or value was available.

Constituent or property	Collin County	Dallas County	Denton County	Ellis County	Hood County	Johnson County	Lamar County	Parker County	Red River County	Tarrant County	Wise County
Silica (SiO_2)	1 - 26	3 - 76	3 - 23	13 - 14	10 - 21	9 - 41	16 - 21	10 - 54	7 - 17	1 - 30	10 - 21
Iron (Fe)	0 - .5	.1- 3.6	0 - .9	--	2.6	0 - 1.7	.2- .5	0 - 10.0	0 - 1.0	0 - 9.9	0.2
Calcium (Ca)	1 - 8	0 - 129	0 - 58	5 - 7	68 - 157	1 - 79	3 - 7	2 - 225	3 - 109	0 - 120	5 - 250
Magnesium (Mg)	0 - 3	0 - 26	0 - 18	1 - 4	2 - 23	0 - 21	1 - 5	1 - 205	1 - 33	0 - 43	2 - 18
Sodium (Na)	245 - 340	30 -1,050	42 - 770	466 - 696	7 - 44	17 - 408	401 - 486	5 - 194	22 - 729	11 - 740	7 - 409
Bicarbonate (HCO_3)	470 - 691	122 - 695	293 - 790	666 - 710	256 - 447	296 - 710	620 - 820	192 - 620	131 - 822	177 - 689	295 - 497
Sulfate (SO_4)	73 - 125	21 -1,711	15 - 494	354 - 864	13 - 74	5 - 280	143 - 192	11 - 167	4 - 191	6 -1,080	31 - 421
Chloride (Cl)	18 - 110	16 - 307	5 - 399	54 - 74	5 - 65	7 - 66	72 - 197	0 - 815	10 - 680	5 - 117	6 - 240
Fluoride (F)	.2- 1.9	.4- 4.0	0 - 3.9	5.4- 7.0	.2- .5	.1- 8.0	3.4- 4.6	0 - 3.2	.1- 6.2	0 - 4.5	.1- 1.1
Nitrate (NO_3)	.2- 2.5	0 - 4.6	0 - 3.2	.4- 3.2	0 - 69	0 - 5.7	.4- 3.5	.4- 135	0 - 2.0	0 - 10.0	.4- 31
Boron (B)	--	2.1	3.0	--	--	.3- 1.4	--	.1- .2	.3	.1- .6	--
Dissolved solids	615 - 847	257 -3,008	310 -2,076	1,250 -1,999	282 - 586	280 -1,071	1,012 -1,237	264 -1,870	200 -1,840	264 -2,176	316 -1,050
Total hardness ($CaCO_3$)	5 - 30	4 - 423	2 - 214	15 - 36	227 - 487	3 - 251	11 - 34	9 -1,400	12 - 350	2 - 401	21 - 699
Percent sodium (%)	95.5- 99.3	29.4- 99.6	30.2- 100	97.5- 98.4	5.6- 24.0	12.9- 99.1	96.4- 98.6	3.5- 97.1	24.0- 98.8	7.1- 99.5	21 - 97.7
pH	8.2- 8.9	7.2- 9.2	7.1- 10.4	8.0- 8.4	6.6- 7.9	7.4- 9.3	8.1- 9.0	6.8- 8.7	7.3- 8.5	7.1- 9.2	6.9- 8.3
Sodium-adsorption ratio (SAR)	23.0- 74.1	1.0- 85.6	1.2- 75.7	49.8- 52.0	.2- 1.0	.4- 52.2	30.8- 57.0	.1- 21.5	.8- 57.6	.2- 68.8	.1- 39.1
Residual sodium carbonate (RSC)	7.4- 10.8	0 - 10.4	.9- 12.1	10.2- 11.3	0 - .3	0 - 11.3	9.6- 13.2	0 - 6.6	0 - 13.2	0 - 10.0	0 - 7.7
Specific conductance (micromhos at 25°C)	1,029 -1,260	451 -5,280	540 -3,770	1,900 -2,270	470 - 905	485 -1,700	1,640 -2,272	461 -3,110	245 -2,180	427 -2,192	518 -1,790

shows the range of constituents and properties of water from representative wells in the Paluxy Formation.

Figure 20 shows the net sand thickness of fresh to slightly saline water-bearing sand in the Paluxy. Net sand thicknesses increase from less than 50 feet (15 m) in Johnson County to 190 feet (58 m) in Denton County. Ordinarily, the most favorable areas for development of ground water would be where the saturated sand is greatest. However, due to the heavy pumpage over the past 30 years, most areas are already overdeveloped and water levels are declining at an alarming rate. The only area that seems available for increased development would be in areas of Fannin and Lamar Counties. The six public supply wells in these counties are located in an area where water from the Woodbine is saline. Well yields in excess of 100 gal/min (6.3 l/s) with pumping levels below 300 feet (91 m) are encountered.

Any Paluxy wells developed in the area of the cone of depression in eastern Tarrant County can expect pumping levels, and in some areas static water levels, to be below the top of the aquifer. Pumps are usually set near the base of the formation. Outside this area and downdip from the outcrop, water levels are declining from 4 to 12 feet (1 to 4 m) per year. Correct spacing of wells is a prerequisite throughout the study region. Any additional development of the Paluxy will result in further lowering of the artesian head in areas where the water levels are still above the formation top. In sone areas, additional development will result in dewatering of the aquifer.

Woodbine Group

The Woodbine Group is an important aquifer in the study region. The outcrop extends in a south-north direction through the center of the report area and then trends to the east parallel to the Red River. The Woodbine dips eastward where it reaches a maximum thickness of about 700 feet (213 m) and has a maximum depth of 2,500 feet (762 m) below land surface. The areal extent of the outcrop and the approximate altitude to the top of the Woodbine are illustrated on Figure 21.

The primary source of ground water in the Woodbine is rainfall on the outcrop area. This area receives an annual rainfall of from 33 inches (84 cm) in the south to 37 inches (94 cm) in the north. Other sources of ground water include surface-water seepage from lakes and streams, such as Lake Grapevine, Garza-Little Elm Reservoir, and the Trinity River tributaries.

Water occurs in saturated sand beds under both water-table and artesian conditions. Water-table conditions occur in or near the outcrop while artesian conditions prevail downdip.

Recharge to the Woodbine occurs in the outcrop area, about 1,200 square miles (3,108 km^2), which consists of a permeable, sandy soil conductive to infiltration of rainfall and seepage from streams. The quantity of recharge to the Woodbine is estimated to be equivalent to less than one inch of precipitation per year on the sandy portion of the outcrop. The movement of water follows an east-southeast direction from the outcrop, generally paralleling the dip of the beds. According to Baker (1960). the average rate of water movement in the Woodbine is estimated to be about 15 feet per year (4.6 m/yr). The hydraulic gradient varies from over 30 feet per mile (5.7 m/km) to less than 13 feet per mile (2.5 m/km) within the study area except for minor local variations and for cones of depression around areas of excessive ground-water pumpage. The hydraulic gradient and a large cone of depression around the city of Sherman are illustrated on Figure 33, which also shows the approximate altitude of water levels in the Woodbine aquifer about 1976.

Discharge from the Woodbine occurs naturally through springs and seeps, evaporation, and transpiration by plants. Evapotranspiration is greatest in the summer and where vegetation is dense. Pumpage of wells constitutes most of the water artificially discharged from the aquifer and includes some flowing wells along the Red River portion of the outcrop. In 1976, about 20,500 acre-feet (25.3 hm^3) of ground water was pumped from the Woodbine in the region.

The coefficients of storage, permeability, and transmissibility and the specific capacity for the Woodbine are shown on Table 4. Aquifer test locations and results are shown on Figure 26. The table was compiled from existing literature and from tests conducted by water-well drillers. Data from aquifer tests were analyzed by using the modified Theis nonequilibrium formula in conjunction with a computer program which provides a means of computing transmissibility from the water-level recovery of a step-drawdown test. The permeability coefficients were computed by dividing the transmissibility by the effective sand thickness. Specific capacities of wells were determined by dividing the yield by the total water-level drawdown measured in the well.

The specific yield was estimated using seismic methods (Duffin and Elder, 1979) in the outcrop under water-table conditions and is on the order of 15 percent. Downd p, where the aquifer is under artesian conditions, the average coefficient of storage is approximately 0.00015, or 1.5 x 10^{-4} The coefficient of storage is dimensionless and indicates the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

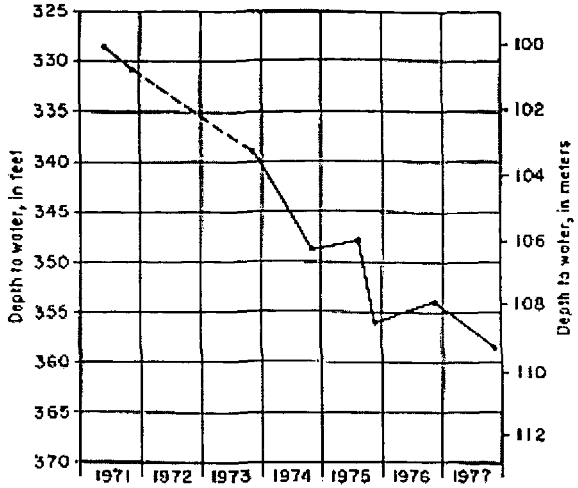
Generally, the more permeable sands of the Woodbine occur on or near the outcrop, where permeability coefficients range from 84 to 167 gallons per day per square foot [(gal/d)/ft^2], or 3,400 to 6,800 liters per day per square meter [(l/d)/m^2]. Farther downdip, a range of 14 to 183 (gal/d)/ft^2, or 570 to 7,500 (l/d)/m^2, was encountered with an average coefficient of permeability of 44 (gal/d)/ft^2, or 1,800 (l/d)/m^2.

Transmissibility values are estimated to be considerably higher along the outcrop where water-table conditions exist. Two tests were conducted on irrigation wells completed in the outcrop in Grayson County and even though the tests were of short duration and thus not completely accurate, values of 7,870 and 16,700 gallons per day per foot [(gal/d)/ft], or 97,800 and 207,400 liters per day per meter [(l/d)/m], were obtained. The 24 remaining tests conducted mainly on public supply wells and utilizing data provided by the well driller showed a range of 1,320 to 14,700 (gal/d)/ft or 16,400 to 182,500 (l/d)/m and an average value of 4,700 (gal/d),lft, or 58,400 (l/d)/m, can be expected. In 1945, the U.S. Geological Survey conducted five pumping tes-ts (drawdown and recovery) on several Woodbine wells owned by the city of Sherman and obtained an average transmissibility of 2,400 (gal/d)/ft, or 29,800 (l/d)/m, and an average coefficient of permeability of 37 (gal/d)/ft^2, or 1,500 (l/d)/m^2.

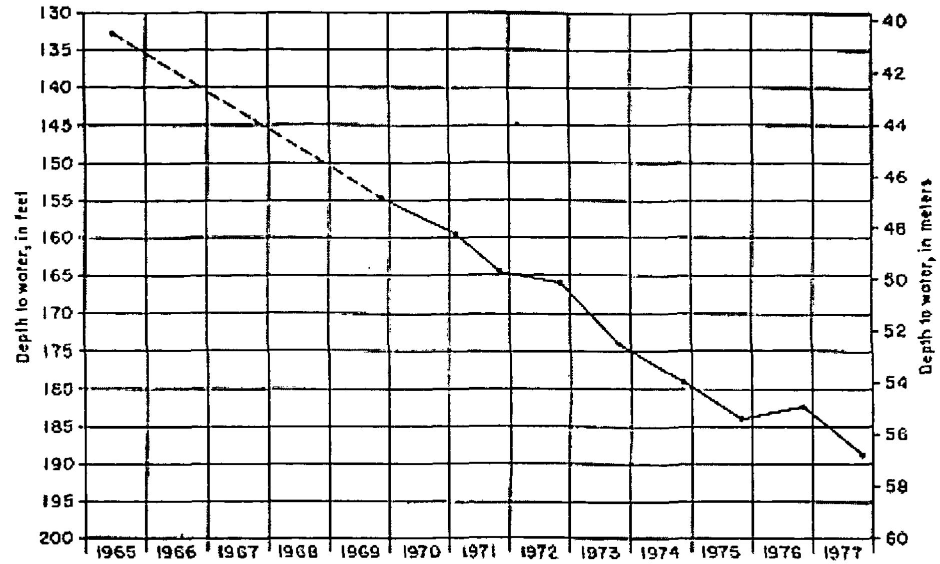
Yields from 336 wells were measured and production ranged form 10 to 1,170 (gal/min) or 0.63 to 74 l/s. The average yield is 106 gal/min (6.7 l/s). Areas of largest production from the Woodbine aquifer are on the outcrop in Denton and Grayson Counties and downdip in Fannin, Grayson, Collin, Dallas, and Ellis Counties. Specific capacities were determined for 139 wells and ranged from 0.2 to 8.7 gallons per minute per foot [(gal/min)/ft], or 0.04 to 1.8 (l/s)/m, of drawdown with an overall average specific capacity of 2.9 (gal/min)/ft, or 0.60 (l/s)/m. The average yields and specific capacities by county are presented below:

County	Number of Wells Measured	Average Yield (gal/ min.	Number of Wells Tested	Average Specific Capacity [(gal/min)/ft]
Collin	20	139	8	2.7
Cooke	8	124	2	1.6
Dallas	67	111	15	2.8
Denton	20	215	9	3.6
Ellis	24	177	11	2.2
Fannin	34	214	21	3.9
Grayson	108	223	5'3	3.2
Johnson	12	51	3	0.9
Tarrant	37	45	15	1.5

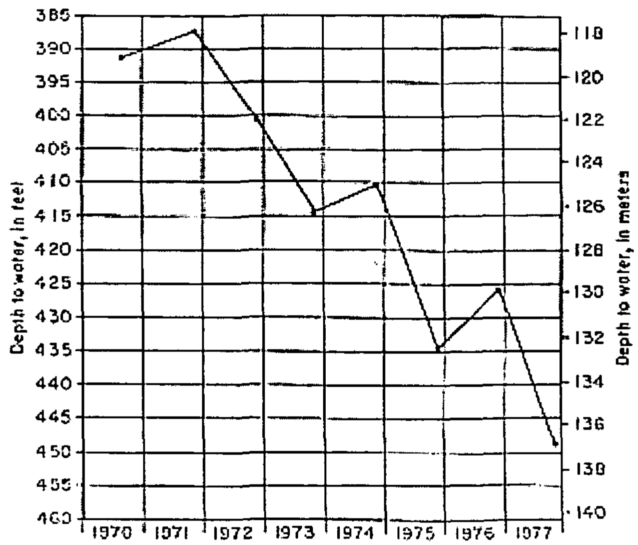
Water levels fluctuate seasonally as indicated by the periodic measurements in a number of observation wells completed in the Woodbine Group. Changes in water levels are illustrated by hydrographs. Water levels in the outcrop seem to recover to static level each year whereas wells in the downdip area reflect yearly declines. Long term water-level changes under water-table and artesian conditions are illustrated by Figures 7 and 10. The approximate altitude of water levels in Woodbine wells around 1955 is shown on Figure 34.



Lamar County
Well RT-17-27-201
depth: 1,675 ft. (511m)



Ellis County
Well JK-32-48-501
depth: 367 ft. (112m)



Grayson County
Well KT-18-27-701
depth: 613 ft. (187m)

Figure 10

Hydrographs of Water Levels in Wells Completed in the Woodbine Group Under Artesian Conditions

In February 1959, well KT-18-20-714 (Grayson County) had a water level of 342 feet (104 m) below ground level. This same well was measured in February 1972 and the static water level had declined to 428 ft (130 m). In April 1977, the water level was 536 feet (163 m) resulting in a net decline of 194 ft (59 m) in just 18 years, or 10.8 feet per year (3.29 m/yr). In Ellis County, well JK-32-48-501 declined 56 feet (17 m) in 12 years, while well JK-33-26-802, further downdip, dropped 138 feet (42 m) in 15 years. However, there are some areas downdip that are not experiencing large declines. For example, well DT-18-50-901 in Collin County declined about 5 feet (1.8 m) in 5 years.

As would be expected, the greatest declines are found in areas where large quantities of water are pumped for industrial and public-supply purposes. This fact, coupled with the low permeability of the water-producing sands, has resulted in a steady decline in the water table. In some downdip areas, especially in the southern part of the study region, the static water level has already dropped below the top of the Woodbine.

Since the initial years of the 20th century, the Woodbine aquifer has been characterized by ever-increasing development. The primary uses of ground water from Woodbine wells are for domestic, livestock, and public-supply purposes. Initial large increases in industrial-water use was followed by a generally, constant reported usage over the last 25 years. The development of ground water for irrigation purposes is relatively new, beginning about 10 years ago with large withdrawals. The increase in production from the Woodbine in the study area is due primarily to the increase in population and in irrigation activities.

In 1976, about 13,750 acre-feet (17.0 hm^3) of ground water was pumped from the Woodbine for public supply, industrial, and irrigation purposes in the study area. This accounts for approximately 20 percent of the ground water pumped from the Woodbine and Trinity Group aquifers for these uses.

Increase in population and home modernization in towns and cities have created a constantly increasing demand for water over the years. This demand is illustrated by Figure 11, which shows the amount of ground water used for public-supply purposes from 1955 to 1976 from the Woodbine and Trinity Group aquifers. The estimated use of ground water from the Woodbine for public supply and industrial purposes from 1955-76 is shown, by county, in Table 13.

In 1976, Grayson County pumped about 4,870 acre-feet (6.01 hm^3) of ground water from the Woodbine for public-supply use. This represents about 57 percent of the 8,560 acre-feet (10.6 hm^3) withdrawn by all counties in the study area. Fannin County was second with about 1,000 acre-feet (1.23 hm^3) of pumpage. The largest, municipal ground-water user is the city of Sherman. In 1933, Sherman pumped 426 acre-feet (0.525 hm^3) from the Woodbine, increasing to 609 acre-feet (0.751 hm^3) in 1943; 1,102 acre-feet (1.36 hm^3) in 1955; 1,795 acre-feet (2.21 hm^3) in 1965; and 3,448 acre-feet (4.25 hm^3) in 1976, which is about 40 percent of the total Woodbine ground-water use in the study region for the year. Many large ground-water users have changed to surface-water supplies, thus decreasing the amount of water pumped from the Woodbine. This decrease is more than offset by the increase in ground-water use by water-supply corporations and smaller, growing towns. A total of 377 public-supply wells were inventoried for this study, which includes those municipal wells no longer in use.

In 1976, approximately 2,581 acre-feet (3.18 hm^3) of ground water was pumped for industrial purposes from the Woodbine, which is about 25 percent of the total quantity of water pumped for industry from the Woodbine and Trinity Group aquifers. About 115 industrial wells were inventoried for this study, most of which are located in Dallas County, where over 50 percent of the industrial pumpage occurs. Industrial pumpage has remained fairly constant with only minor fluctuations occurring from 1955 to 1976, as illustrated on Figure 12 and in Table 13. Some of the declines in industrial usage may be misleading because many businesses purchase ground water from cities where it is reported as municipal pumpage.

In 1977, approximately 135 irrigation wells pumped 2,717 acre-feet (3.35 hm^3) of ground water for irrigation purposes from the Woodbine Group. The irrigation pumpage represents about 20 percent of the total ground water pumped from the Woodbine during 1976 in the study region. This pumpage was principally from Grayson and northern Denton Counties, which accounted for 64 percent of the irrigation pumpage. Irrigation ground-water pumpage in these and adjacent counties for the period 1970-77 is illustrated on Table 5. In most cases, these wells are pumped from 4 to 6 weeks annually and the water is generally used to irrigate peanuts and grasses.

The quantity of ground water used for irrigation was determined in part on power and yield tests conducted on selected irrigation wells, and in part on using measured yields in conjunction with the owner's estimate of the time the irrigation well was pumped annually. The results and data collected from the power and yield tests are given in Table 7. The industrial and municipal use was determined by compiling the data on

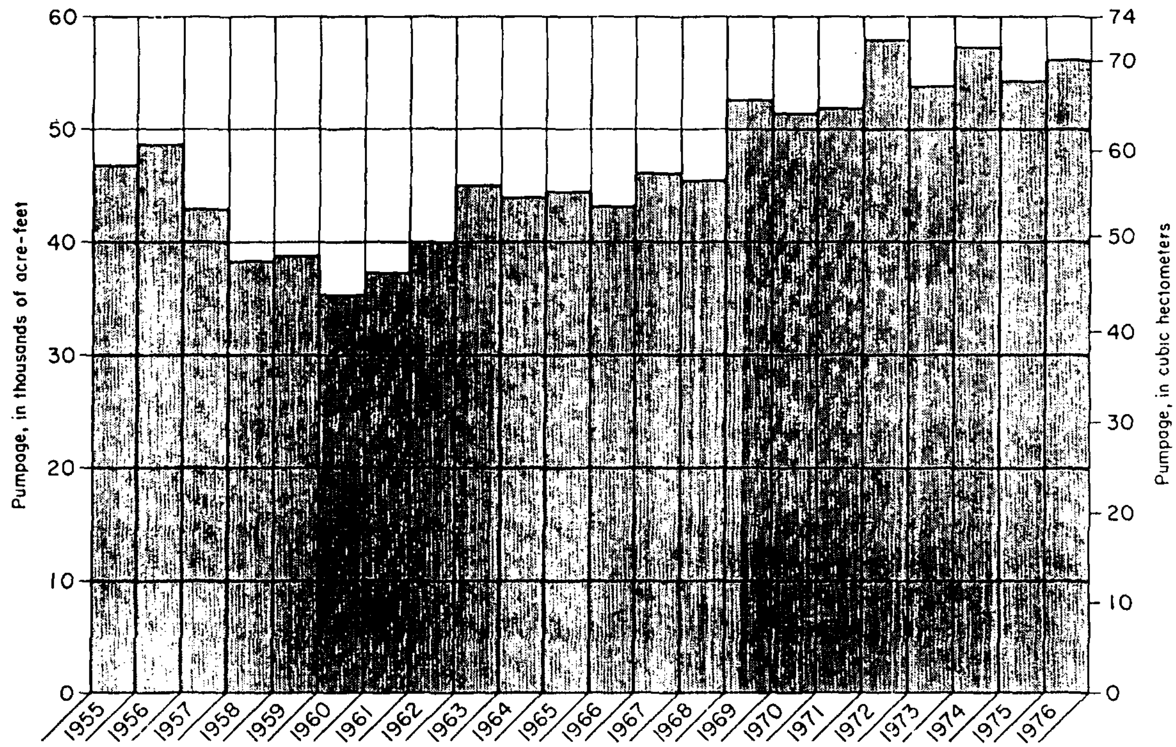


Figure 11.—Public Supply Ground-Water Pumpage From the Woodbine and Trinity Group Aquifers, 1955-76

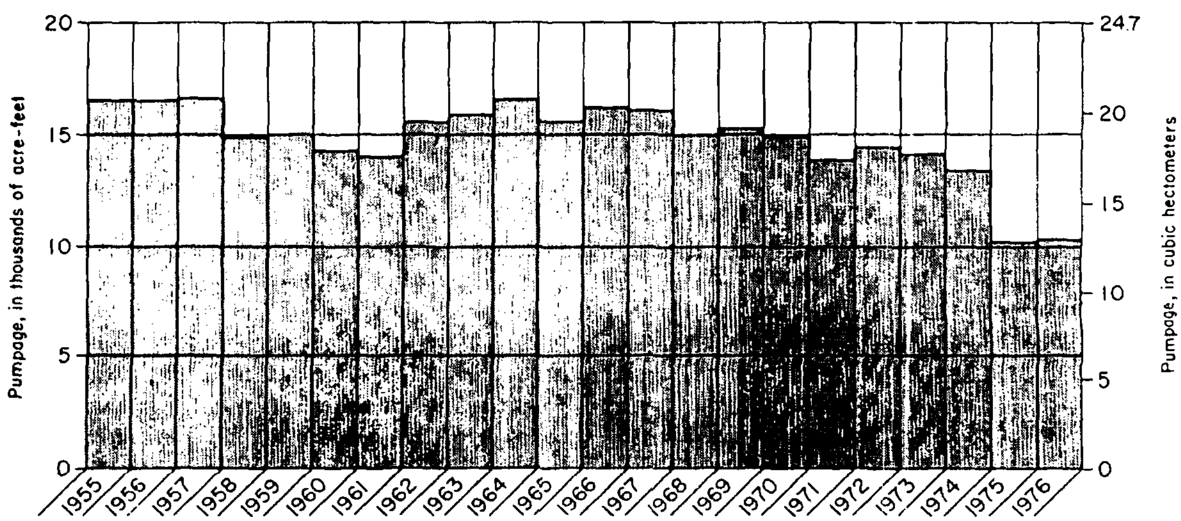


Figure 12.—Industrial Ground-Water Pumpage From the Woodbine and Trinity Group Aquifers, 1955-76

returned questionnaires mailed annually by the Department to the various surface- and ground-water users.

There was little irrigation ground-water use prior to 1965. However, since 1965, many wells have been drilled and ground-water withdrawals continue to rise. The amount of water pumped from the Woodbine for irrigation doubled during the years 1970 to 1977.

Water quality in wells completed on or near the outcrop of the Woodbine is fresh and of good quality

Table 13.--Estimated Use of Ground Water for Public Supply and Industrial Purposes From the Woodbine Group, 1955-76

Use: PS, public supply; Ind, industrial. Values are in acre-feet.

County	Use	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
Collin	PS	716.2	696.0	301.3	327.6	312.3	267.7	242.9	195.7	237.4	242.6	247.5
	Ind	--	--	--	--	--	--	--	--	--	--	--
Dallas	PS	1,819.6	1,828.0	1,686.0	1,448.5	1,560.4	1,556.2	1,344.4	1,436.6	1,483.3	1,350.1	1,454.0
	Ind	1,596.1	1,596.1	1,596.1	1,441.7	1,221.0	1,119.0	1,070.7	1,577.1	1,031.2	1,327.3	1,632.6
Denton	PS	--	--	--	1.0	1.0	95.0	61.9	64.0	86.4	112.2	118.4
	Ind	--	--	--	--	--	--	--	--	--	--	--
Ellis	PS	1,558.0	1,530.0	1,616.6	1,420.7	1,298.1	1,317.8	1,328.4	1,314.0	1,376.4	1,406.7	1,534.0
	Ind	--	--	--	--	--	140.0	140.0	140.0	280.0	280.0	280.0
Fannin	PS	1,380.6	1,494.7	1,335.2	1,397.4	1,484.5	1,378.2	1,417.1	1,394.8	1,503.8	1,518.9	1,494.4
	Ind	--	--	--	--	--	40.0	70.0	90.0	90.0	90.0	95.0
Grayson	PS	1,862.3	2,037.6	1,866.6	2,004.2	2,131.5	1,864.4	2,010.7	2,237.6	2,563.2	2,560.6	2,729.3
	Ind	593.7	593.7	593.7	1,033.0	1,318.4	886.6	630.6	592.5	730.9	758.6	798.6
Hunt	PS	28.0	39.3	46.0	33.6	37.0	39.9	34.2	36.3	43.2	44.6	45.4
Johnson	PS	112.3	66.6	59.0	87.3	75.4	100.4	64.8	58.0	58.3	65.8	66.0
Kaufman	PS	132.6	100.7	100.7	84.0	81.4	80.7	76.7	61.4	67.5	67.5	22.1
Lamar	PS	--	--	--	--	--	--	--	--	--	3.5	20.7
Navarro	PS	183.0	147.6	159.8	179.7	158.9	119.3	99.1	126.8	120.9	116.3	108.6
Tarrant	PS	80.0	80.0	80.0	64.0	79.3	65.4	45.4	80.0	90.0	90.0	81.6
	Ind	1.2	1.2	1.2	1.8	1.3	1.5	1.2	1.1	1.0	.8	.9
Totals	PS	7,872.6	8,020.5	7,251.2	7,048.0	7,219.8	6,885.0	6,745.6	7,005.2	7,630.4	7,578.8	7,922.0
	Ind	2,191.0	2,191.0	2,191.0	2,476.5	2,540.7	2,189.1	1,932.5	2,400.7	2,133.1	2,456.7	2,807.1
	PS and Ind	10,063.6	10,211.5	9,442.2	9,524.5	9,760.5	9,074.1	8,678.1	9,405.9	9,763.5	10,035.5	10,729.1

County	Use	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	Totals
Collin	PS	309.9	365.9	360.9	406.1	487.7	616.7	739.9	664.6	741.3	809.0	599.6	9,888.8
	Ind	--	--	--	100.1	42.9	34.0	34.0	34.0	34.0	34.0	34.0	347.0
Dallas	PS	1,457.5	1,576.8	1,429.5	1,412.0	1,159.8	989.6	891.6	896.7	910.6	887.0	835.5	29,413.7
	Ind	1,463.1	1,390.5	1,332.6	913.1	1,009.7	1,005.2	1,158.3	1,088.5	1,214.7	1,187.2	1,326.0	28,297.8
Denton	PS	123.2	129.2	161.2	156.7	81.9	46.7	73.1	63.3	75.3	137.1	193.0	1,780.6
	Ind	--	--	--	--	--	--	1.6	1.6	4.7	57.7	7.2	72.8
Ellis	PS	1,190.7	539.6	528.1	569.4	614.1	656.7	763.4	724.8	825.3	860.8	716.2	23,629.8
	Ind	280.0	280.0	336.0	336.0	336.0	336.0	471.2	624.6	732.6	726.8	700.4	6,419.6
Fannin	PS	1,543.6	1,479.8	1,127.5	1,962.0	1,091.4	1,827.9	1,843.7	874.4	997.5	927.5	993.4	30,468.3
	Ind	95.1	159.6	198.2	83.8	82.2	143.7	122.9	118.3	120.3	125.0	117.1	1,861.3
Grayson	PS	3,059.6	3,233.8	3,436.9	4,038.8	4,195.2	4,360.7	4,365.3	4,432.5	4,630.5	4,474.5	4,672.0	68,967.8
	Ind	760.2	732.4	745.6	760.8	730.5	573.3	495.1	530.5	429.5	337.9	395.9	15,024.0
Hunt	PS	55.3	64.9	78.7	87.8	105.9	102.6	126.0	116.0	129.6	134.6	131.3	1,560.2
Johnson	PS	86.8	66.5	64.6	85.1	67.6	70.8	74.9	70.9	65.2	158.7	72.4	1,697.4
Kaufman	PS	--	--	--	--	--	--	--	--	--	--	--	815.3
Lamar	PS	10.6	11.5	13.1	15.0	11.6	10.2	13.2	13.4	13.6	17.9	19.7	174.0
Navarro	PS	112.0	161.6	128.9	97.4	102.2	100.7	171.5	101.5	105.4	110.4	112.1	2,823.7
Tarrant	PS	81.8	85.7	2.5	3.7	6.2	8.6	6.8	7.7	7.4	7.0	14.3	1,087.4
	Ind	.8	.3	.1	--	.3	167.0	50.3	.3	.3	.3	--	233.1
Totals	PS	8,031.0	7,715.3	7,327.9	8,830.0	7,919.6	8,787.2	9,069.4	7,965.8	8,501.7	8,524.5	8,559.5	172,411.0
	Ind	2,599.2	2,562.8	2,616.8	2,197.8	2,205.6	2,263.2	2,333.4	2,397.8	2,536.1	2,468.9	2,580.6	52,271.6
	PS and Ind	10,630.2	10,278.1	9,944.7	11,027.8	10,125.2	11,050.4	11,402.8	10,363.6	11,037.8	10,993.4	11,140.1	224,682.6

with the exception of high iron concentrations occurring in the upper Woodbine sands or in improperly completed wells. This iron contamination can be alleviated by insur ng that the well penetrates the entire Woodbine Group, or at least to the middle of the Woodbine, and cementing off the upper member of the group. It is not uncommon for water from wells in the upper part of the Woodbine to contain iron concentrations in excess of 3.0 mg/l. Water from 9 wells contained concentrations greater than 10 mg/l. Water quality deteriorates rapidly downdip from the outcrop with concentrations increasing in sodium, chloride, and bicarbonate. The downdip limit of fresh to slightly saline water (Figure 33) occurs approximately 35 miles (56 km) downdip from the outcrop. Along the outcrop, well water contains an average dissolved-solids content of 550 mg/l, while water from areas farther downdip approach the 2,000 mg/l level. Of the more than 800 analyses tabulated, 325 (40 percent) exceeded 1,000 mg/l, and 90 (11 percent) contained more the 2,000 mg/l dissolved solids. Only 90 samples exceeded 300 mg/l chloride and 263 (32 percent) of the analyses exceeded 300 mg/l sulfate. High nitrate levels are not naturally found in the Woodbine and only a few, shallow dug wells exceeded 45 mg/l. Over 80 percent of the analyses collected had a total hardness as calcium carbonate of less than 60 mg/l, giving the water a general classification as soft. Table 14 shows the range of constituents in ground water from selected wells in the Woodbine Group.

The specific conductance of irrigation waters from the northern Woodbine outcrop ranges from 298 to 1,720 micromhos per cubic centimeter (cm^3) at 25°C (77°F). The five samples containing over 750 micromhos per cm^3 were taken in the Sadler area of Grayson County. Other water samples in this vicinity were between 600 and 750 micromhos per cm^3. The remaining 28 samples showed an average specific conductance of 470 micromhos per cm^3, well below the 750 level.

The diagram for the classification of irrigation waters from the Woodbine (Figure 13) shows that the sodium hazard is low, with an SAR ranging from 0.4 to 7.8. Only two samples fell into the medium catagory while the major ty of samples had an SAR below 2. According to classification by percent sodium, all but five samples were below 60 percent and only three exceeded 75 percent.

Of the 33 samples taken, only 13 were tested for boron. The range was from 0 to 0.4, giving the water in this area an excellent rating for even sensitive crops. RSC was calculated for all samples and a range of 0 to 2.6 was determined. Only four samples had an RSC in excess of 0.9 me/l and of these, three were considered marginal and one not safe. The wells from which these samples were taken are pumped about 4 to 6 weeks per year and the water is generally used to irrigate peanuts and grasses.

Blossom Sand

The Blossom Sand aquifer crops out in central Fannin County and extends eastward through Lamar and Red River Counties. Its thickness can range up to about 400 feet (122 m). In general, ground water from the Blossom is fairly high in dissolved-solids content (120 to 2,030 mg/l) and is soft.

Only four of the eleven municipal wells found in the study area are in operation. The largest ground-water user is the city of Clarksville, Red River County. Yields range from 45 to 500 gal/min (2.8 to 31.5 l/s). Specific capacities average slightly more than 1 (gal/min)/ft, or 0.21 (l/s)/m. Several pumping tests conducted on wells in Clarksville showed an average transmissibility of 3,800 (gal/d)/ft, or 47,200 (l/d)/m, and an average

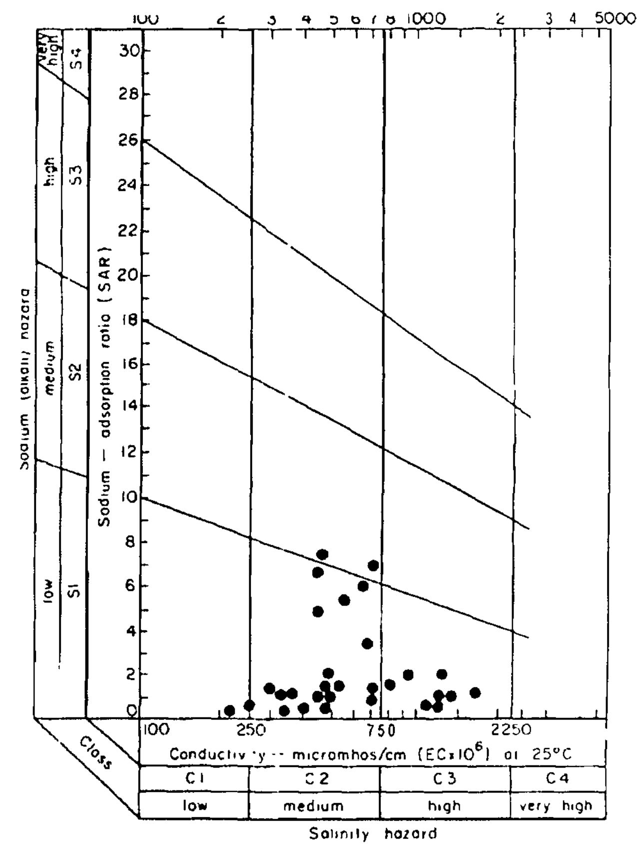


Figure 13.-Diagram for the Classification of Irrigation Waters Showing Quality of Water From Wells Completed in the outcrop of the Woodbine Group (After United States Salinity Laboratory Staff, 1954, p. 80)

Table 14.--Range of Constituents in Ground Water From Selected Wells in the Woodbine Group

Analyses given are in milligrams per liter except percent sodium, specific conductance, pH, SAR, and RSC.

Single values appear where only one analysis or value was available.

Constituent or property	Collin County	Dallas County	Denton County	Ellis County	Fannin County	Grayson County	Johnson County	Kaufman County	Lamar County	Navarro County	Tarrant County
Silica (SiO_2)	5 - 49	5 - 59	0 - 33	8 - 29	1 - 79	3 - 40	8 - 27	6 - 68	15 - 39	11 - 18	6 - 21
Iron (Fe)	0 - 3.4	0 - 6.5	.1- 21.2	0 - .9	0 - 4.7	0 - 18.0	0 - 7.2	0 - .7	9	.1- 5.8	.4- 13.0
Calcium (Ca)	1 - 52	0 - 105	0 - 269	0 - 14	0 - 34	0 - 230	3 - 405	6 - 28	2 - 34	3 - 11	1 - 194
Magnesium (Mg)	0 - 35	0 - 24	0 - 101	0 - 11	0 - 53	0 - 89	1 - 89	2 - 26	1 - 9	1 - 5	0 - 22
Sodium (Na)	150 -1,370	113 - 930	15 - 790	208 -1,200	151 -1,318	9 -1,070	53 - 447	897 -1,356	20 - 405	570 -1,390	5 - 408
Bicarbonate (HCO_3)	246 -1,130	165 -1,050	77 - 800	370 -1,060	317 -1,150	54 - 850	79 - 580	1,100 -1,210	52 - 590	705 -1,170	40 - 529
Sulfate (SO_4)	37 - 479	44 - 824	17 - 530	16 - 586	30 - 406	3 -1,460	60 - 580	269 - 453	5 - 157	69 - 520	4 - 560
Chloride (Cl)	12 - 640	10 - 610	12 - 492	17 -1,310	13 -1,633	4 - 910	18 - 139	543 -1,210	47 - 155	127 -1,420	7 - 154
Fluoride (F)	.6- 4.0	0 - 5.7	.1- 4.1	0 - 7.9	0 - 4.6	.1- 3.0	.3- 2.0	1.8- 4.7	.1 1.9	2.1 6.1	.1 2.5
Nitrate (NO_3)	0 - 7	0 - 31.0	.2- 294	0 - 50.0	0 - 7.0	0 - 20.0	0 - 56	.4- 14.0	.4- 2.4	.2- 11.0	.4- 44
Boron (B)	--	.1- 4.2	.3	1.5- 4.8	--	0 - 1.7	.7- .8	--	--	5.7	.3
Dissolved solids	377 -2,611	338 -2,430	141 -2,133	429 -3,032	386 -3,256	106 -3,386	367 -1,234	2,563 -3,480	161 -1,038	1,572 -3,494	72 -1,220
Total hardness ($CaCO_3$)	2 - 108	3 - 359	2 - 510	4 - 450	1 - 303	0 - 940	13 - 700	24 - 177	8 - 120	11 - 50	4 - 550
Percent sodium (%)	91.9- 99.3	67.9- 99.7	18.9- 100	42.8- 100	90.4- 99.6	9.9- 99.6	27.8- 98.6	91.7- 99.1	30 - 98.9	98.0- 99.1	9.8- 98.3
pH	7.5- 9.2	6.9- 8.9	6.6- 9.1	7.1- 8.8	7.5- 8.9	6.5- 9.4	6.4- 8.5	8.0- 8.2	6.1- 8.3	7.5- 8.5	6.4- 9.1
Sodium-adsorption ratio (SAR)	13.0- 93.9	5.3- 129.5	.7- 76.6	3.1- 101.6	21.3- 88.4	.3- 101.1	1.8- 51.8	29.3- 109.2	.9- 56.6	58.1- 98.0	.2- 36.5
Residual sodium carbonate (RSC)	3.8- 17.8	1.0- 16.0	0 - 12.6	5.7- 17.0	5.0- 18.4	0 - 13.5	0 - 9.2	17.5- 19.2	0 - 9.5	11 - 18.4	0 - 8.3
Specific conductance (micromhos at 25°C)	609 -4,710	697 -3,549	220 -3,844	895 -3,616	624 -2,760	162 -4,020	551 -1,830	4,860	251 -1,650	2,055 -6,060	139 -1,750

permeability of 45 (gal/d)/ft^2, or 1,830 (l/d)/m^2. The coefficient of storage was calculated to be 4.5 X10^{-5}.

Public-supply pumpage within the study area was 561 acre-feet (0.692 hm^3); all but 1 acre-foot (0.001 hm^3) was withdrawn by the city of Clarksville. Water levels have declined since development at Clarksville began in 1905 which indicates pumpage exceeds effective recharge (Baker and others, 1963).

Nacatoch Sand

The outcrop of the Nacatoch Sand extends in a northerly direction from Limestone to Hunt County where it trends to the northeast and passes through Red River County into Bowie County. It ranges in thickness from 350 feet (107 m) to 500 feet (152 m). The depth to the top of the aquifer is about 800 feet (244 m) along the southward extent of the fresh to slightly saline water line near the boundary of Red River and Bowie Counties.

Of the 52 public-supply wells and 5 industrial wells located in the study area which were completed in the Nacatoch, 20 are no longer used. Yields measured in municipal and industrial wells ranged from 20 gal/min (1.3 l/s) to 500 gai,'min (31.5 l/s) with an average of 135 gal/min (8.5 l/s). Specific capacities obtained from 15 wells ranged from 0.3 to 9.3 (gal/min)/ft, or 0.06 to 1.9 (l/s)/m. Several pumping tests conducted on Nacatoch wells owned by the city of Commerce (Table 4) showed an average transmissibility of 2,500 (gal/d)/ft, or 31,000 (l/d)/m, and coefficients of permeability ranging from 26 to 53 (gal/d)/ft^2, or 1,060 to 21,200 (l/d)/m^2.

Flowing wells exist in Red River and Bowie Counties. Dissolvea-solids content generally ranges from 100 to 1,700 mg/l. A total of 50 chemical analyses were obtained from inventoried wells and included in this study.

Pumpage has steadily increased over the years and water levels have declined since development began in 1914 (Baker and others, 1963). Municipal and industrial pumpage increased from 687 acre-feet (0.47 hm^3) in 1955 to 1,591 acre-feet (1.96 hm^3) in 1965, and to 2,135 acre-feet (2.63 hm^3] in 1975.

AVAILABILITY OF GROUND WATER

Methods Used to Determine Availability

The procedural steps used to appraise the ground-water availability of the Trinity and Woodbine aquifers were to review pertinent publications and then select an evaluation method or combination of methods to derive the average annual ground-water availability. These methods generally fell into three basic catagories, namely; (l) steady-state flow under the supposition that water levels did not change with time and natural recharge balanced discharge; (2) rate of depletion of ground-water that is recoverable from storage; and (3) circumstances requiring geohydrological judgements or assumptions. In general, only fresh to slightly saline ground water containing less than 3,000 mg/l dissolved solids was evaluated. A discussion of methodologies developed to appraise the ground water available in the study area follows.

Steady-State Flow Methods

Although steady-state flow does not generally happen in nature, the concept that it is approximated in nature is beneficial to the development of analyical methods used to evaluate the available ground water in an aquifer. If so, the discovery by Henri Darcy in 1856 that the rate of water flowing through sand is proportional to the hydraulic gradient is applicable here (Lohman, 1972). This relation is known as Darcy's Law, and Bennett (1976) states that it "relates specific discharge, or discharge per unit area, to the gradient of hydraulic head. It is the fundamental relation governing steady-state flow in porous media." Darcy's Law may be expressed by the equation:

$$q = Q/A = -K\ dh/dl.$$

where q is the specific discharge per unit area, Q/A; Q is the rate of discharge or flow, A is the cross-sectional area through which the discharge or flow passes and is normal to the direction of flow; K is the hydraulic conductivity or permeability of the porous medium; and dh/dl is the head gradient or hydraulic gradient. Values for the parameters of discharge, Q; applicable area, A; permeability, K; and the hydraulic gradient, dh/dl were obtained by the best procedures depending on the form of the available data.

The trough method is a geometric application of Darcy's Law and is used to evaluate the sustainable annual yield or annual effective recharge available from an artesian (confined) aquifer (Klemt and others, 1975, p. 11-12). This steady-state flow method assumes the lowering of water levels to the top of the aquifer downdip from the outcrop to a maximum of 400 feet (112 m) below land surface, but not below the top of the aquifer. The trough axis would be an imaginary line connecting innumerable points of discharge along which the top of the aquifer is approximately the same depth below land surface, roughly parallel to the outcrop of the aquifer. The quantity of water that the aquifer will transmit under the hydraulic gradients established between the recharge area and the innumerable points of discharge along an approximate line of discharge, provides an index to the aquifer's maximum effective recharge capability if the water is available as precipitation.

Rate of Depletion of Ground Water That is Recoverable From Storage

The methodology used to determine the depletion rate of recoverable ground-water storage differs for artesian and water-table aquifers. In the case of the Trinity aquifer, the amount of artesian storage proposed for development was determined by constructing a present thickness map of the recoverable artesian storage zone, computing the total volume in the depletion zone, and multiplying it by the storage coefficient. With due consideration given to the transmission capacity of the Trinity aquifer and to pumping lift costs, the lowering of water levels by innumerable discharge points lying in the area between the aquifer outcrop and the downdip limit of fresh to slightly saline water was limited to a maximum level of 100 feet (30 m) above the top of the aquifer (Figure 14). The annual storage depletion rate was calculated by dividing the recoverable storage by 53 years which is the depletable or planning period to the year 2030 (Texas Water Development Board, 1977, Vol. 1, p. 1 I-65). This depletion rate was then added to the annual effective recharge to give the average annual ground-water availability.

Circumstances Requiring Geohydrological Judgements or Assumptions

In order to make a determination of ground-water or assumptions availability utilizing the methodologies

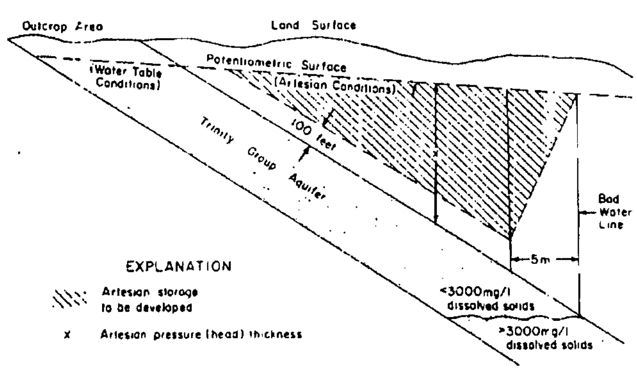


Figure 14.-Diagrammatic Cross Section Through a Confined Aquifer Showing Depletable Artesian Ground-Water Storage

just discussed, it was necessary to make certain judgements or assumptions based on unique aquifer attributes. For example, a judgement was made as to whether or not the transmission capacity of the aquifer was compatible to the effective recharge which is based on a percentage of the mean annual precipitation. Judgements or assumptions employed in these methods will become more explicit in the Trinity and Woodbine aquifer discussions which follow.

Trinity Group

The ground water available for future development was determined collectively for the Antlers, Paluxy, and Twin Mountains Formations and called the Trinity Group aquifer (Table 1). The annual effective recharge or transmission capacity of the Trinity Group aquifer in the study area was determined using the trough method. The methodology is based on pumpage under assumed conditions and is related mainly to the ability of the aquifer to transmit water to the areas of pumpage. To compute the amount of water available from the Trinity Group aquifer, several assumptions had to be made.

It was assumed that water levels in the outcrop would not decline. An imaginary line of discharge was constructed approximately parallel to the outcrop where the depth to the top of the Trinity Group was 400 feet (122 m) below land surface. The line of discharge was approximately 135 miles (217 km) long, extending from Johnson County west of Cleburne, through Fort Worth in Tarrant County, through Denton County west of Denton, and through Grayson County east of Gainesville. All the recharge was assumed to occur in the middle of the outcrop along a line parallel to the strike. The line of discharge averages 13 miles (21 km) from the assumed line source of recharge. Pumping along the line of discharge will lower water levels to the top of the Trinity Group, which is 400 feet (122 m) below land surface. The hydraulic gradient under which ground water is being transmitted through the aquifer is the difference in the altitude of the water level in the outcrop and the altitude of the top of the Trinity where it is 400 feet (122 m) below land surface divided by the distance between these points of altitude, which is approximately 13 miles (21 km). It was also assumed that recharge along the outcrop will be uniformly transmitted to the line of discharge and that the slope of the piezometric surface will be constant after drawdown to the 400-foot (122 m) level. The average coefficient of transmissibility used for the Trinity Group aquifer was 11,000 (gal/d)/ft or 136,600 (l/d)/m.

Using these assumptions and provided that sufficient water is available as recharge, it was determined that approximately 1.5 percent of the average annual precipitation falling on the outcrop, or approximately 51,000 acre-feet (62.9 hm^3), can be transmitted through the Trinity Group aquifer to the line of discharge. This is the computed amount of water that can be pumped annually by wells located downdip from the outcrop in the study area. The 1.5 percent was judged to be acceptable since effective recharge for the Trinity Group in North Texas is probably not greater than 5 percent.

The thickness of artesian storage was determined by using a geologic structure map of the top of the Trinity Group aquifer and the 1977 water-level observation well measurements. The thickness equals the distance between the potentiometric surface and 100 feet (30 m) above the top of the aquifer (Figure 14). The top of the Trinity Group is represented by the Antlers Formation in the northern part of the study area and by the Paluxy Formation south of the Antlers. Contouring of the recoverable artesian storage area was limited as follows: (1) within 5 miles (8 km) of the downdip limit of fresh to slightly saline water; (2) within 5 miles (8 km) of the Texas-Oklahoma border; and (3) where 100 feet (30 m) of artesian head was present above the top of the Trinity Group aquifer. The area of recoverable artesian storage was determined by using a planimeter. The area was multiplied by the thickness of artesian storage and then by the coefficient of storage to give the volume of recoverable storage. A conservative artesian storage coefficient of 1×10^{-4} was used. In January 1977, it was estimated that slightly more than 646,000 acre-feet (797 hm^3) of ground water in the study area could be withdrawn from storage.

The total annual ground-water availability of the Trinity Group aquifer was determined by dividing the volume of recoverable storage by 53 years (January 1, 1977 through December 31, 2029) and adding it to the annual effective recharge. The total annual ground-water availability for the Trinity Group aquifer in the study area to the year 2030 is about 63,000 acre-feet (77.7 hm^3) which consists of 51,000 acre-feet (62.9 hm^3) of annual effective recharge and 12,000 acre-feet (14.8 hm^3) of recoverable storage.

Woodbine Group

In calculating the estimated transmission capacity of the Woodbine aquifer, the following assumptions were made: (a) pumpage would draw water levels down to the top of the aquifer where it is 400 feet below land surface; (b) ground water passes through a vertical section of the aquifer which is 180 miles long and located 5 to 10 miles downdip from the outcrop along a line through Ellis, Dallas, Denton, Collin, Grayson, Fannin, and Lamar Counties; (c) the average transmissibility for the aquifer is 4,700 (gal/d)/ft or 58,365 (l/d)/m.

Based on the above assumption, approximately 24,500 acre-feet (30.2 hm^3) of water can theoretically be transmitted by the Woodbine aquifer in the study area to pumping wells downdip from the outcrop. This amount of water can be pumped annually and is less than 5 percent of the estimated average annual precipitation of 35 inches available to the outcrop area as recharge.

Nacatoch and Blossom Sands

The methodology used to appraise the annual ground-water availability of the Nacatoch and Blossom Sands was a comparison of pumpage and water-level trends.

In regions of heavy pumpage around Clarksville in Red River County and Commerce in Hunt County, water levels have declined steadily. These annual water-level declines are a direct result of pumpage exceeding the effective recharge. After analyzing water-level data presented by Baker and others (1963), it is estimated that the average annual ground-water availability, as effective recharge, within the study area for both of the aquifers is 1,619 acre-feet (2 hm^3). This includes an annual effective recharge for the Nacatoch Sand of 994 acre-feet (1.23 hm^3) and 625 acre-feet (0.771 hm^3) for the Blossom Sand.

WELL CONSTRUCTION

Well construction in the study region is generally based on water requirements and economics. Some of the well designs used to produce ground water from the sand and gravel aquifers in the study area are illustrated on Figure 15.

Within the Trinity Group outcrop area, irrigation wells producing from the Antlers, Paluxy, and Twin Mountains Formations are generally of medium to high capacity (15-470 gal/min) (0.95-30 l/s), cased, and gravel packed. The casing is usually slotted opposite the desired water-bearing unit. Irrigation wells completed in the Woodbine Group are of high capacity (30-900 gal/min) (1.9-57 l/s); however, in some areas of the outcrop, the lower Woodbine is non-(productive, and yields are small (lO-50 gal/min) (0.63-13.2 l/s). Other than the high capacities, completion of wells in the Trinity and Woodbine Groups are similar. The diameter of the well

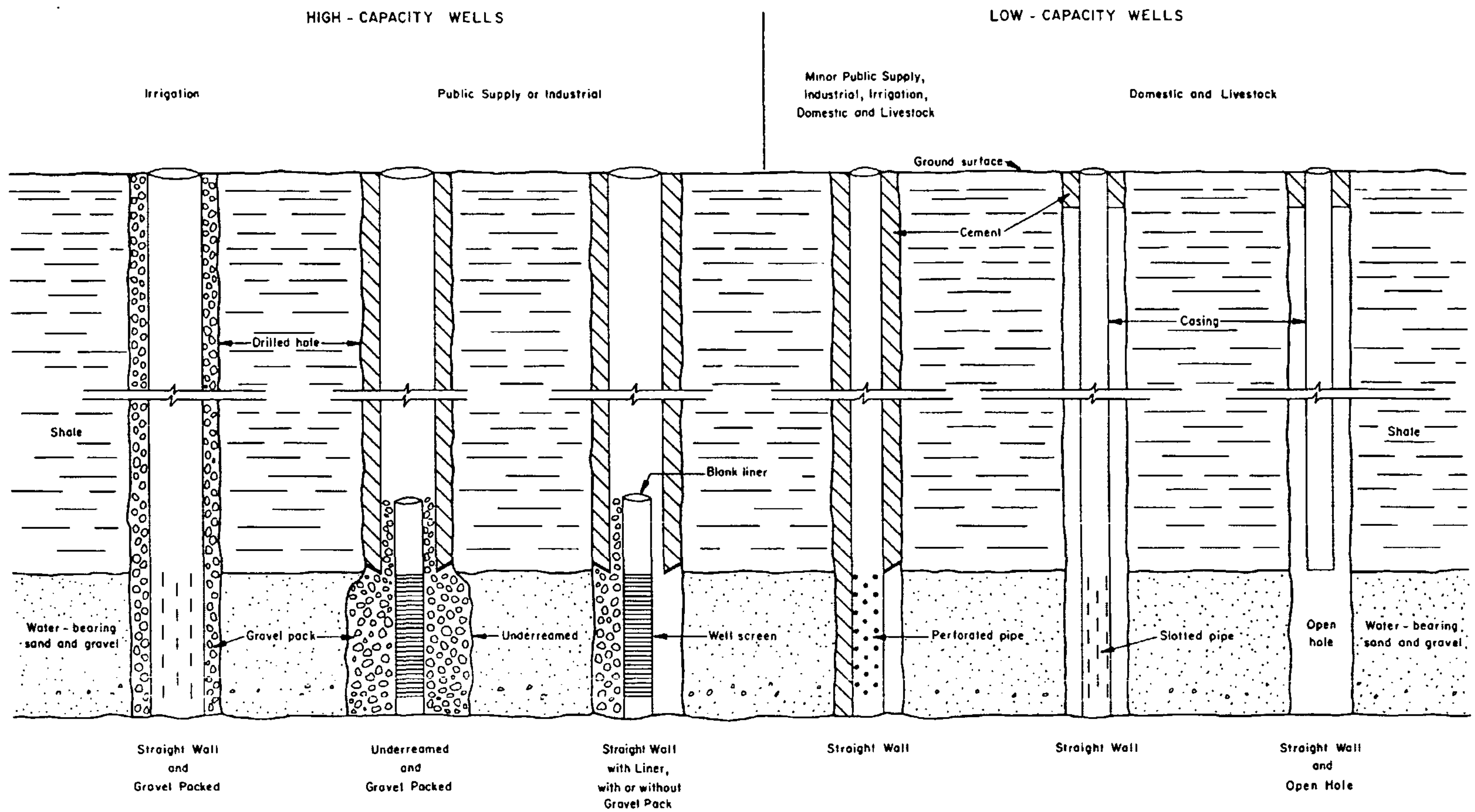


Figure 15
Diagrams of Well Construction

casing varies with the formation and the pumping capacity. In general, the most common size of casing is between 6 and 8 inches (15 and 20 cm). High-capacity Woodbine irrigation wells fall in the 12- to 16-inch (30.5- to 40.6-cm) diameter range. A number of high-capacity Twin Mountains wells in Hood County are 10 inches (25 cm) in diameter.

Generally, public supply and industrial wells are straight walled, cased, and may be cemented from the surface to the top of the desired water-bearing unit. Casing is either slotted or perforated opposite the water-producing interval or selectively screened with intervening blank liner. Large-capacity wells are often underreamed and Gravel packed. Small-capacity wells, in some cases, are cemented from top to bottom and the casing is gun perforated opposite the water-bearing strata. Open-hole completions are rarely found in large-capacity wells in this area. Usually a large diameter casing is used at tne surface and cemented into place to restrict seepage of surface water into the bore hole. Generally, the casing opposite the water-bearing strata ranges from 3 to 12 inches (7.6 to 30 cm) in diameter.

Domestic and livestock wells are generally straight walled, cased from top to bottom, slotted or perforated, and cemented around the top of the casing. In some areas, the wells are gravel packed, and in others, the casing extends only to the top of the producing beds and left as an "open hole" type completion. Casing used in these small-capacity wells generally ranges from 3 to 8 inches (7.6 to 20 cm) in cliameter.

Improperly completed wells can lead to problems such as insufficient yield and poor water quality, which may not only be a problem affecting the well in question, but can also result in contamination of wells in the surrounding area. One of the most common problems occurring in the study region involves water from the Woodbine that is used for domestic purposes. The upper part, and sometimes the middle part, of the Woodbine aquifer contains water that is high in dissolved iron. An iron concentration of more than the recommended upper limit of 0.3 mg/l will stain laundry, utensils, and plumbing fixtures reddish brown and also impart an unpleasant taste. To eliminate this problem, the upper strata, and in some areas the middle strata, of the Woodbine are cemented off and the wells are completed in the lower Woodbine, which contains better quality water. Wells completed in this part also have a higher capacity.

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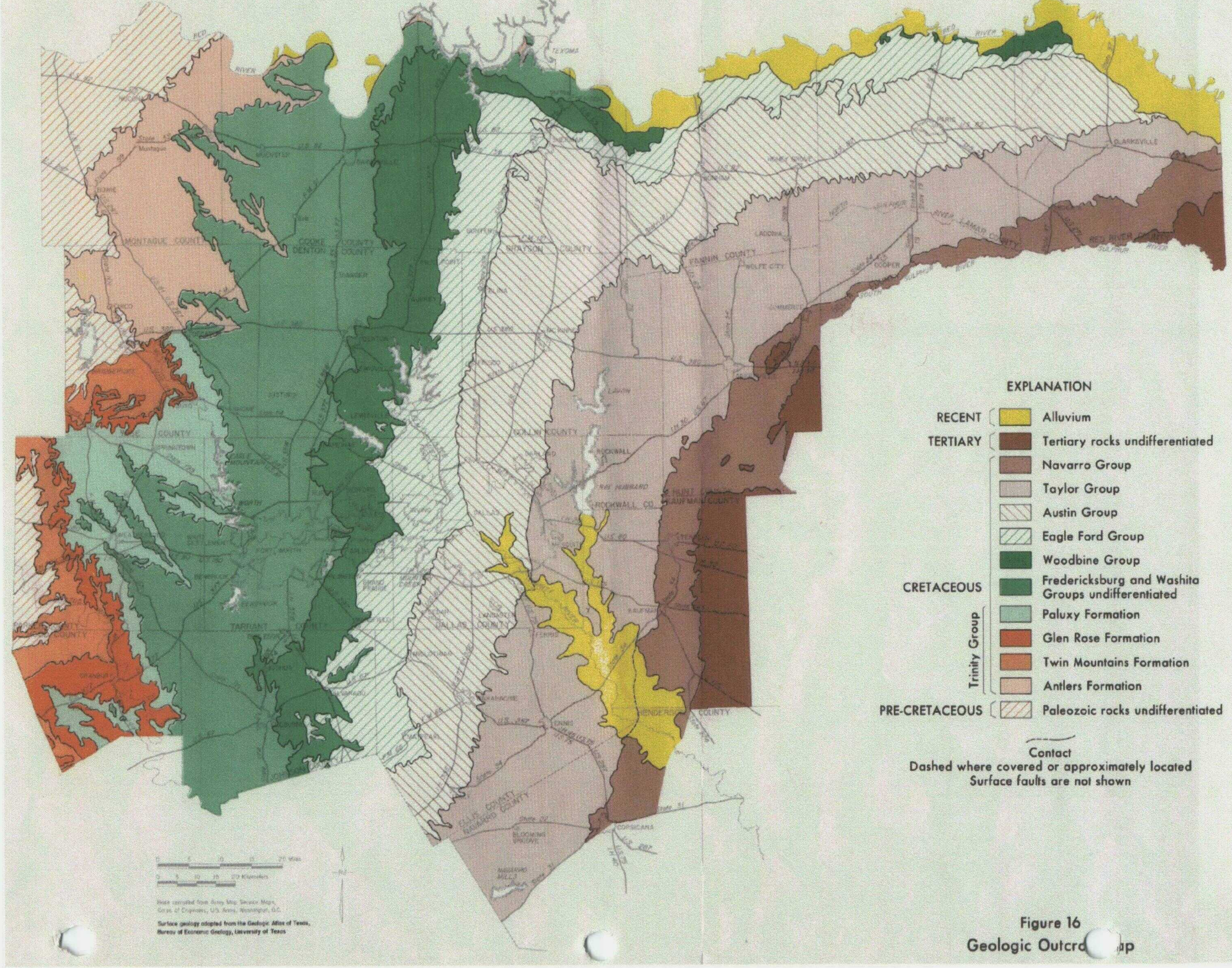


Figure 16
Geologic Outcro[illegible]ap

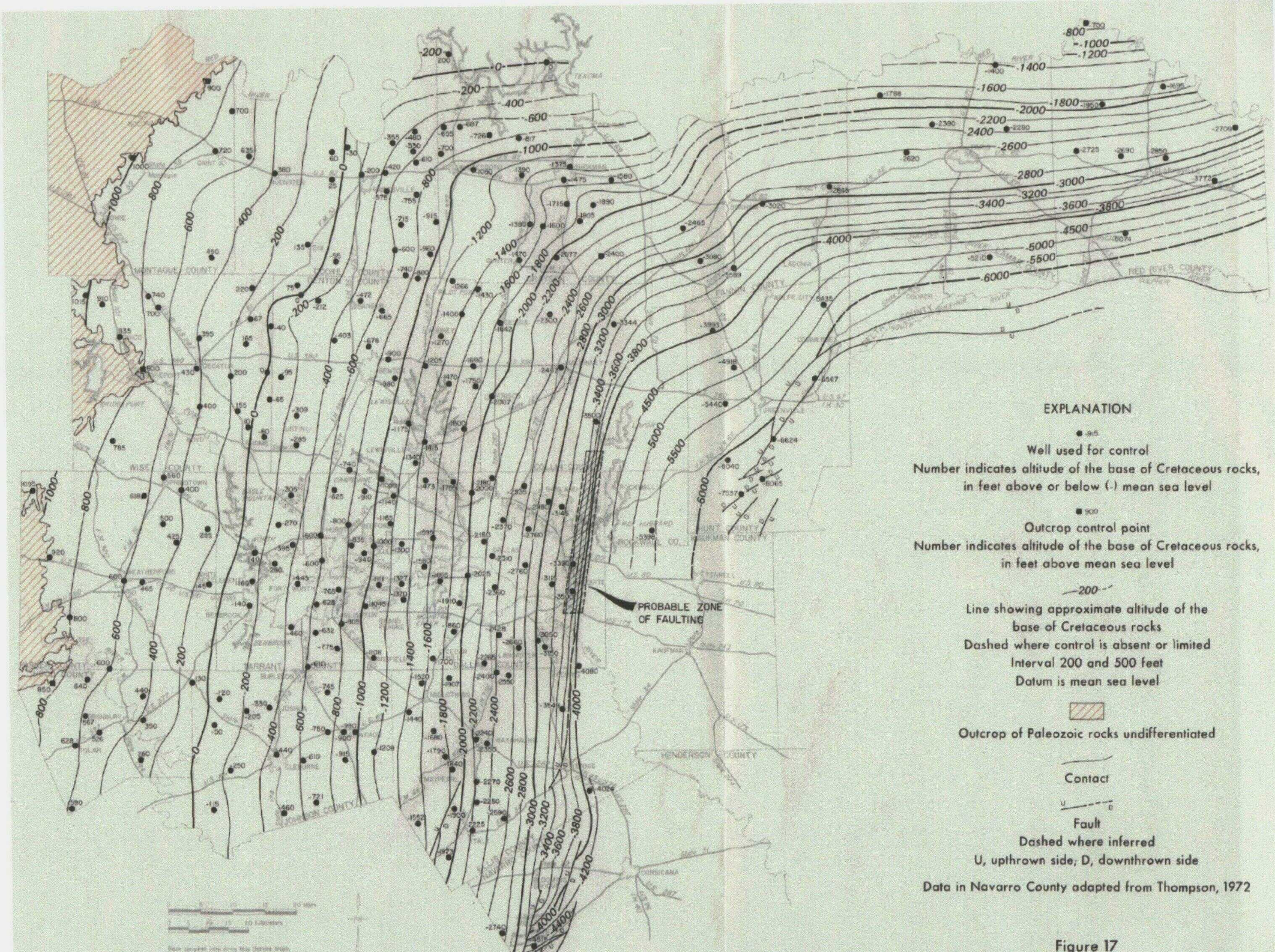


Figure 17
Approximate Altitude of the Base of Cretaceous Rocks

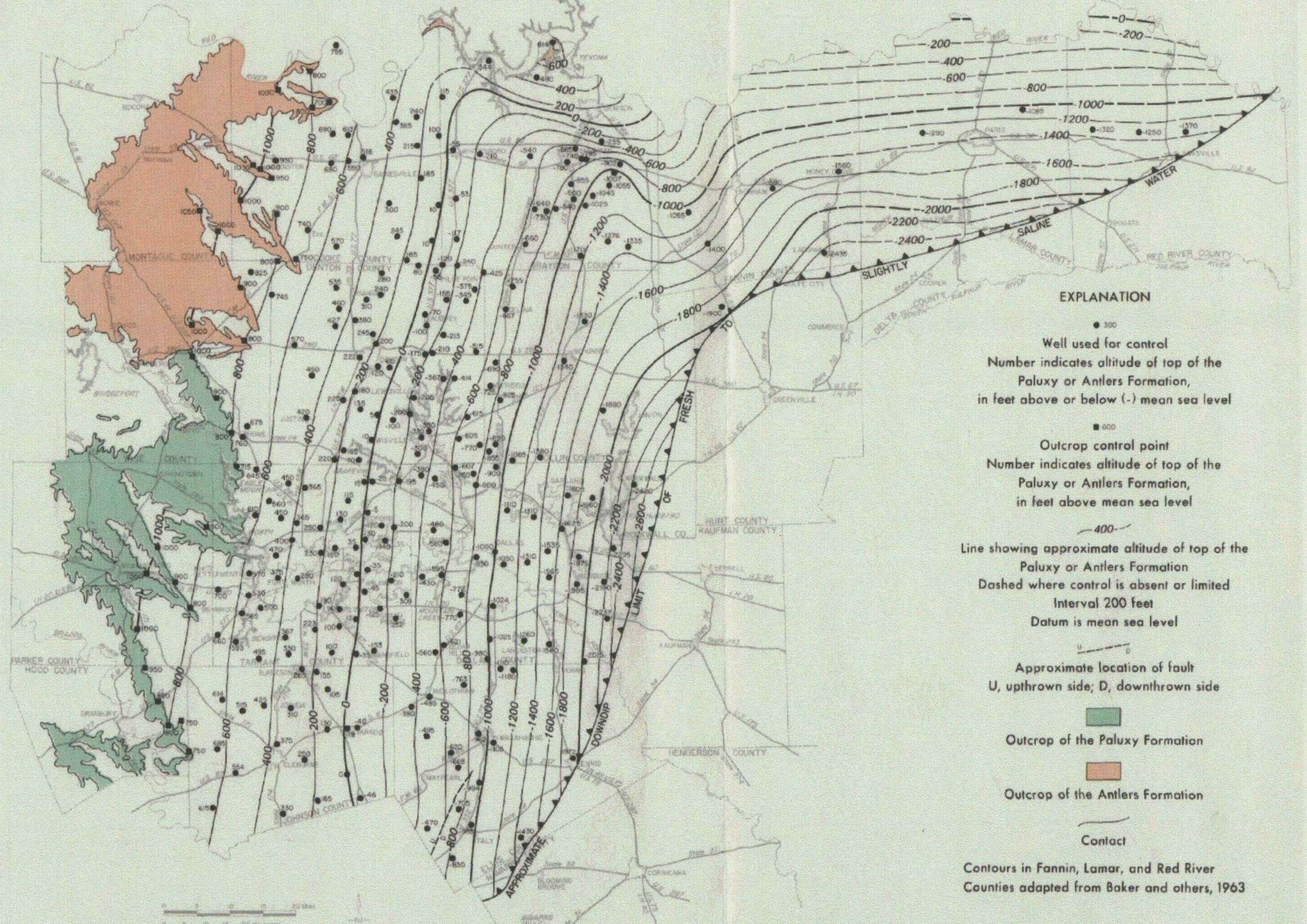


Figure 18

Approximate Altitude of the Top of the Paluxy and Antlers Formations

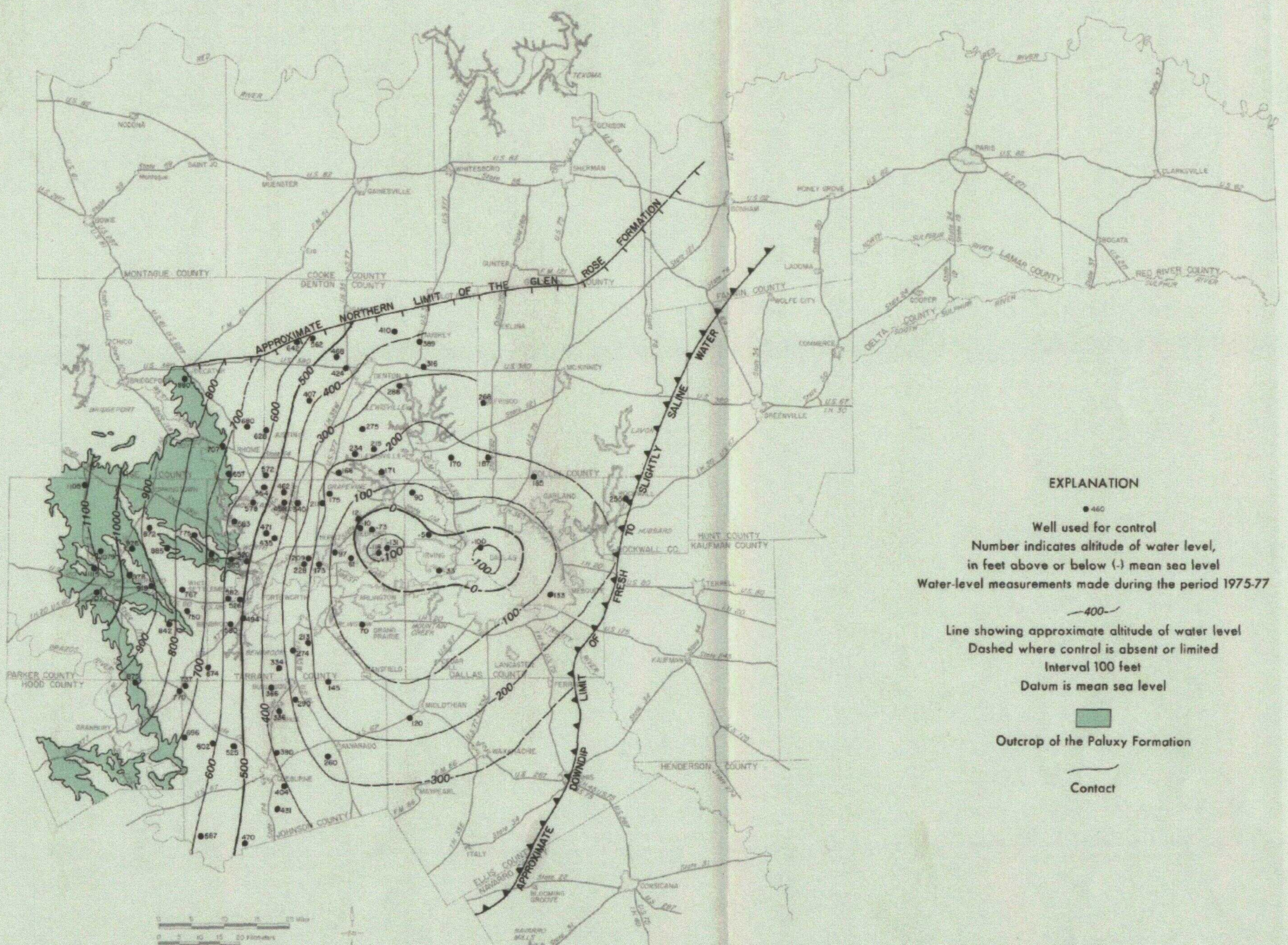


Figure 31

Approximate Altitude of Water Levels in the Paluxy Aquifer, About

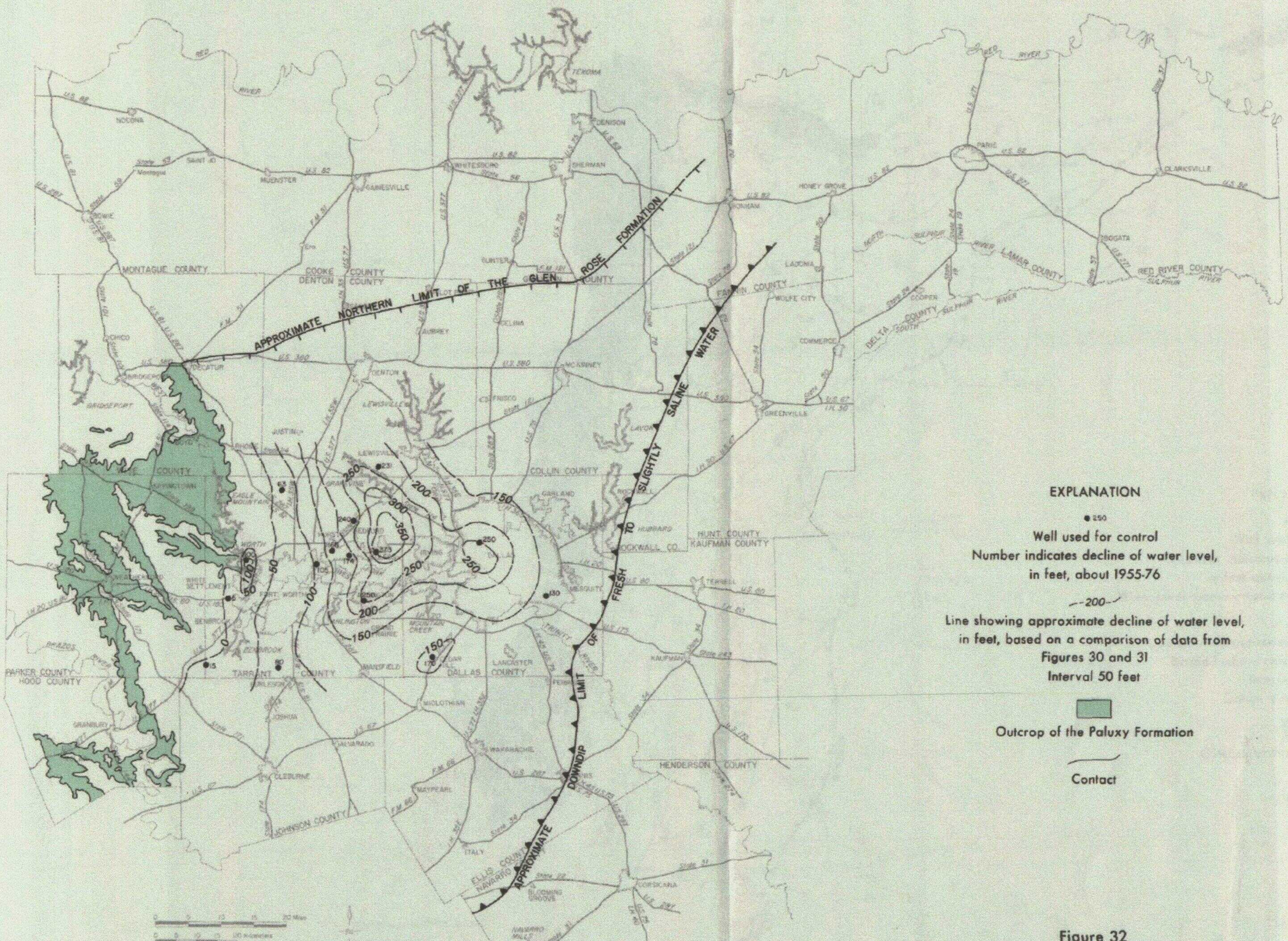


Figure 32
Approximate Water-Level Decline in the Area of Heavy Municipal Pumpage in the Paluxy Aquifer, About 1955-76

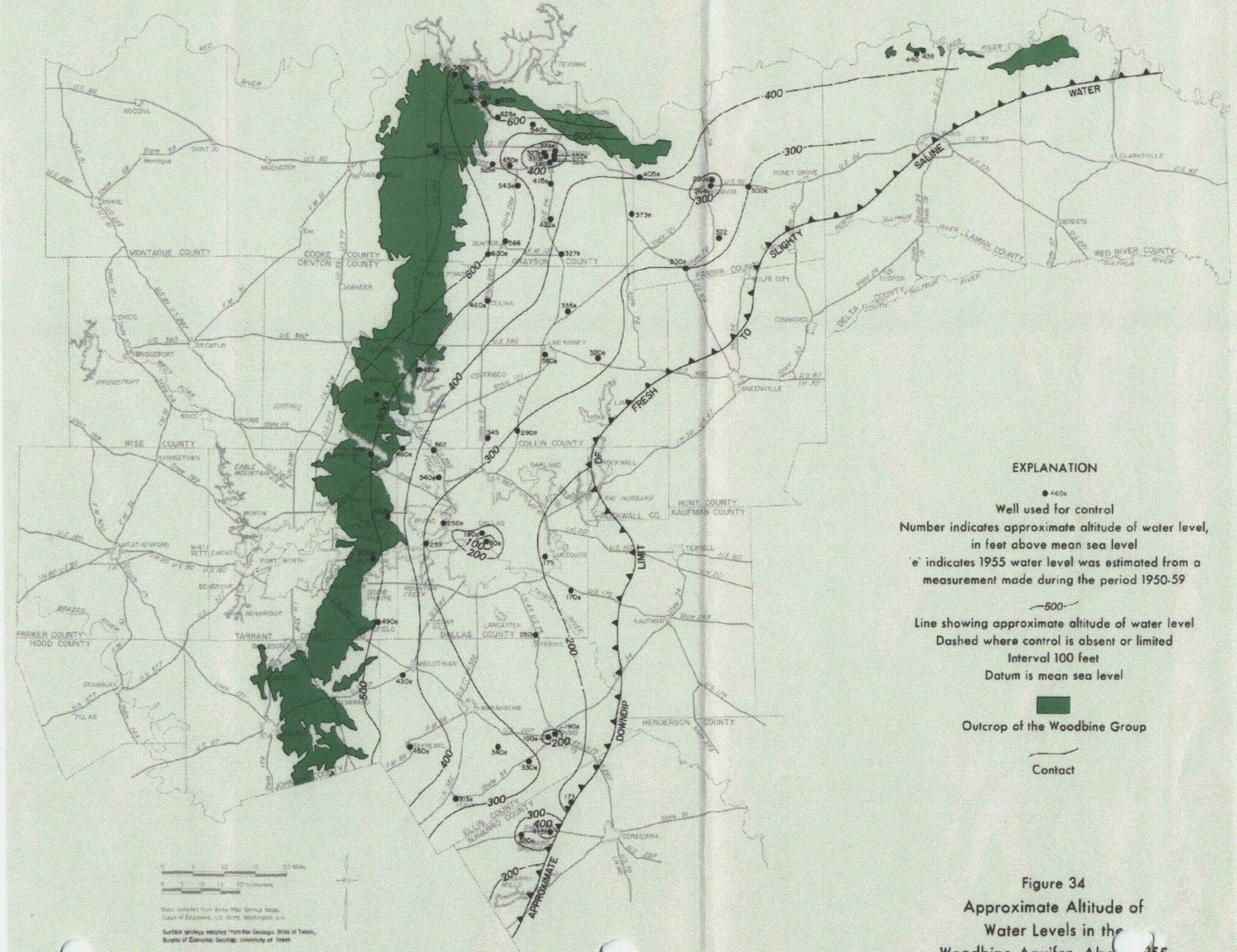


Figure 34
Approximate Altitude of Water Levels in the Woodbine Aquifer, About 1955

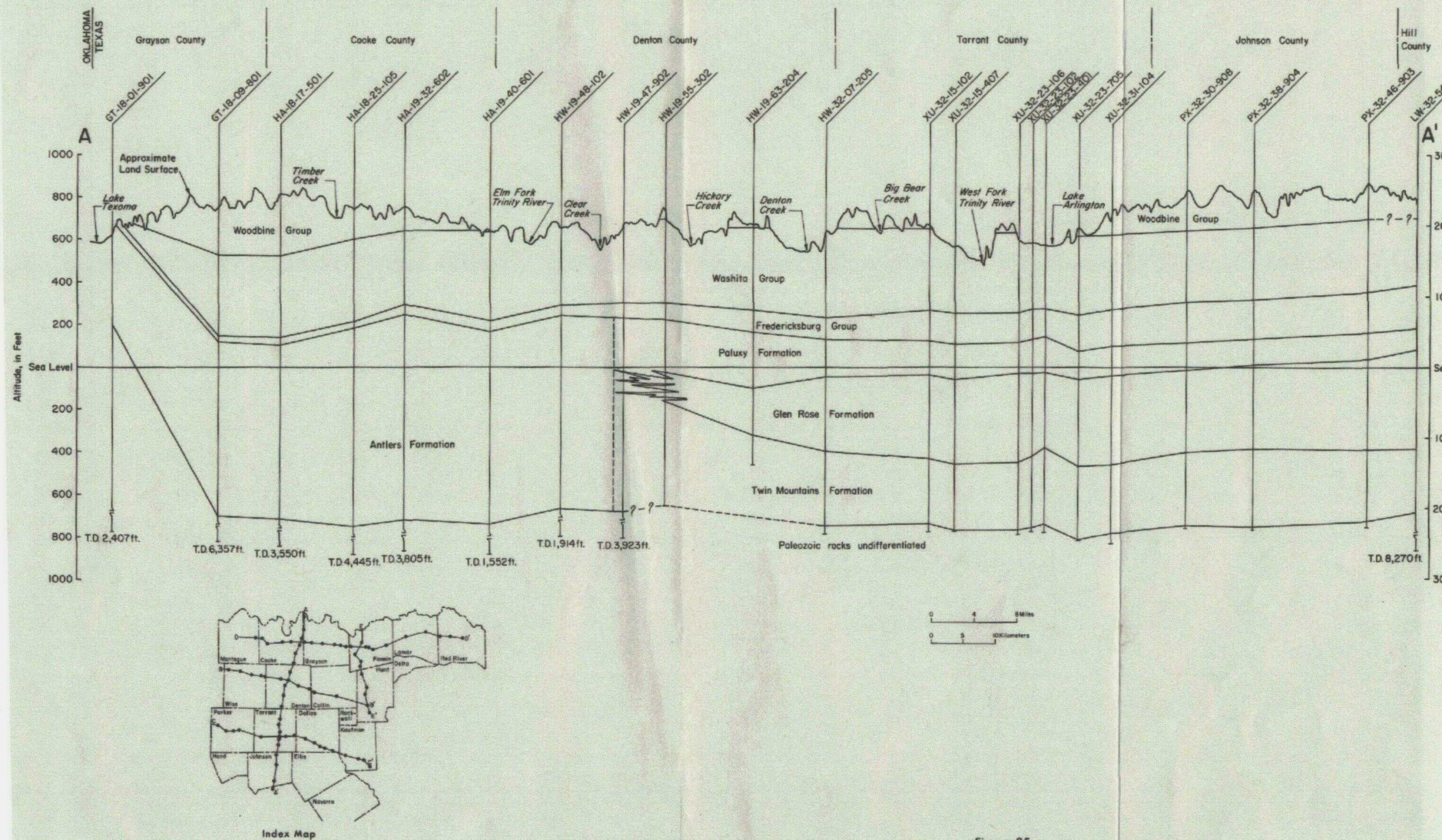


Figure 35

Geologic Section A-A'

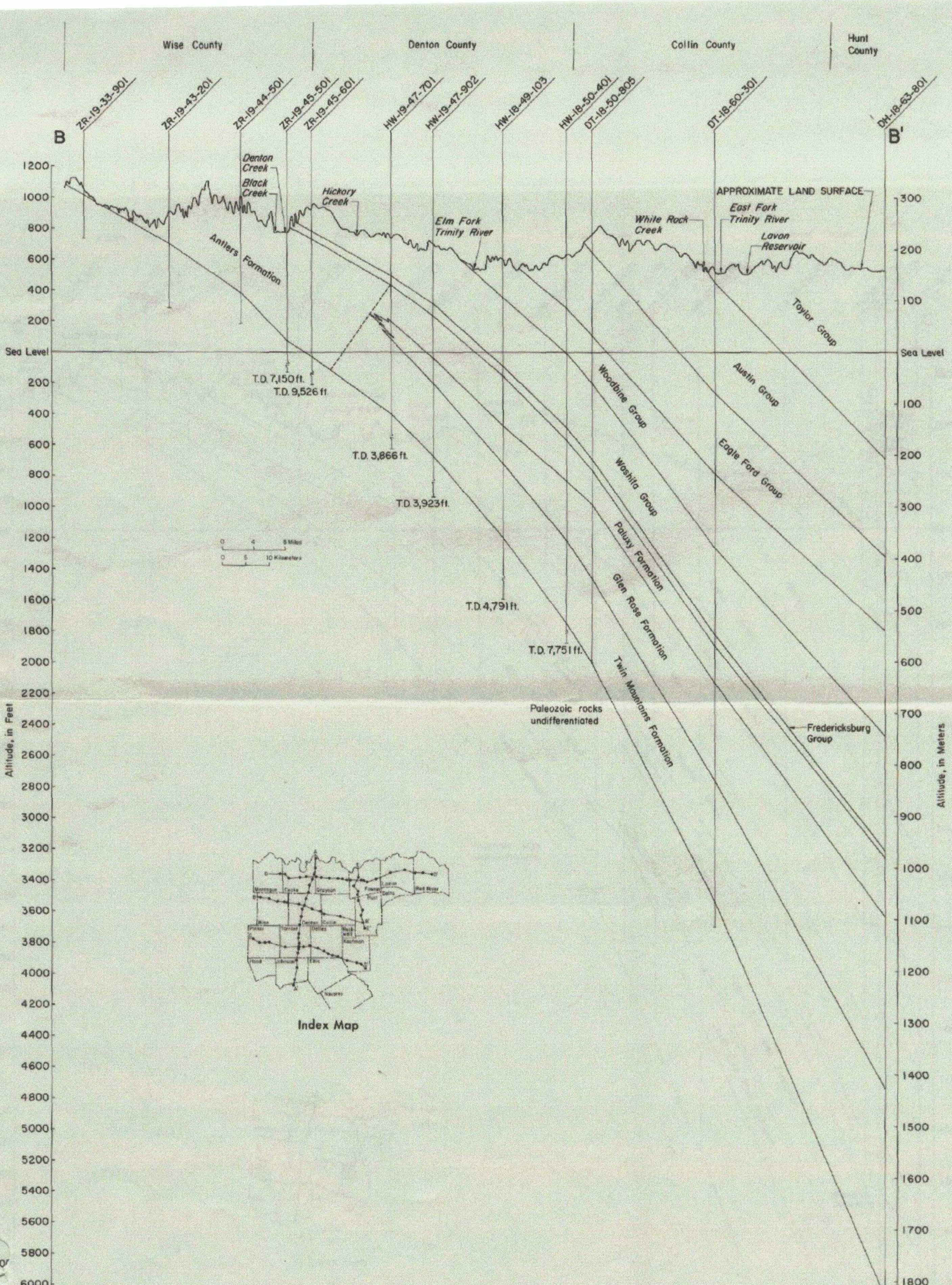


Figure 36
Geologic Section B-B'

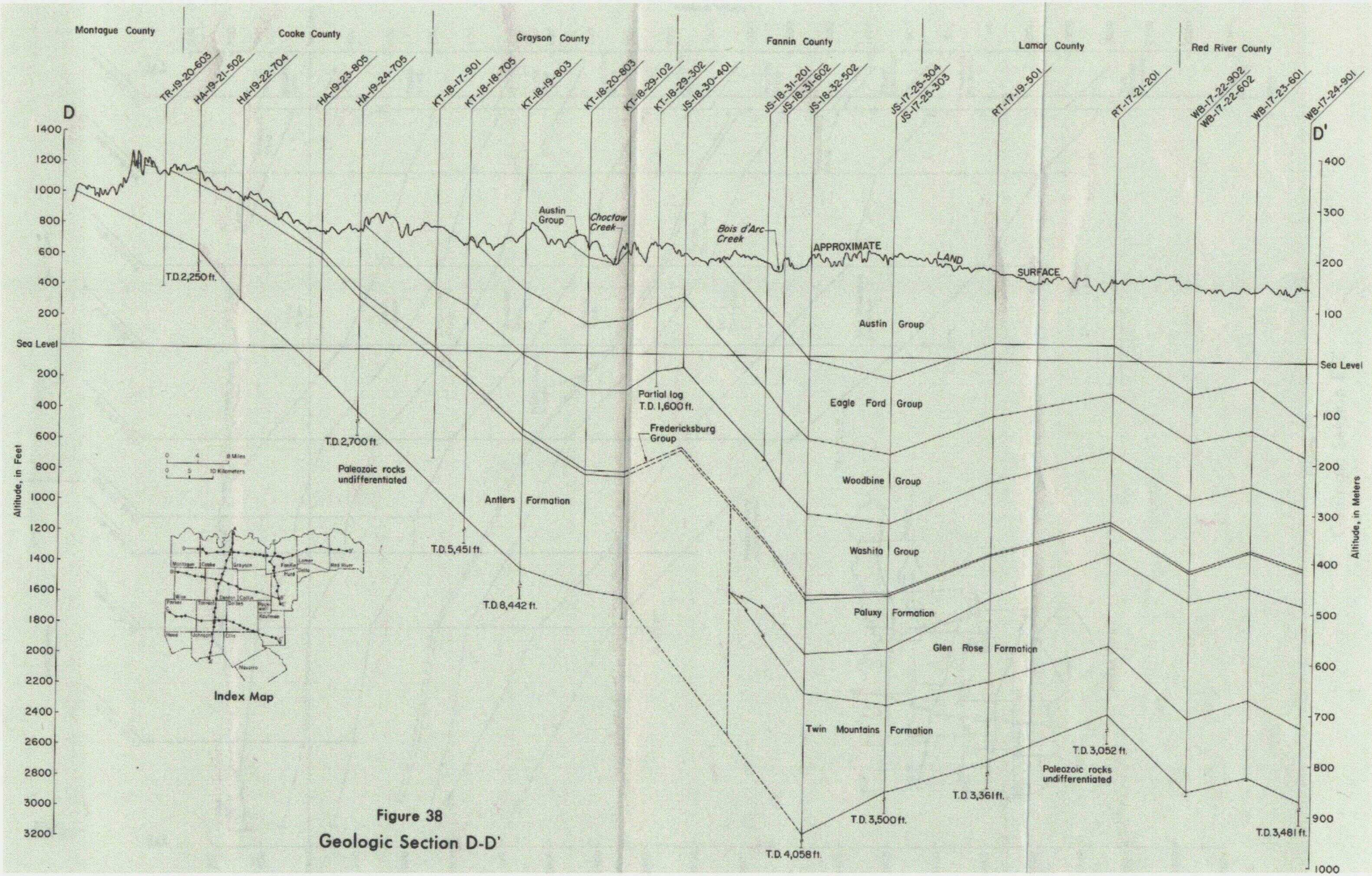


Figure 38

Geologic Section D-D'

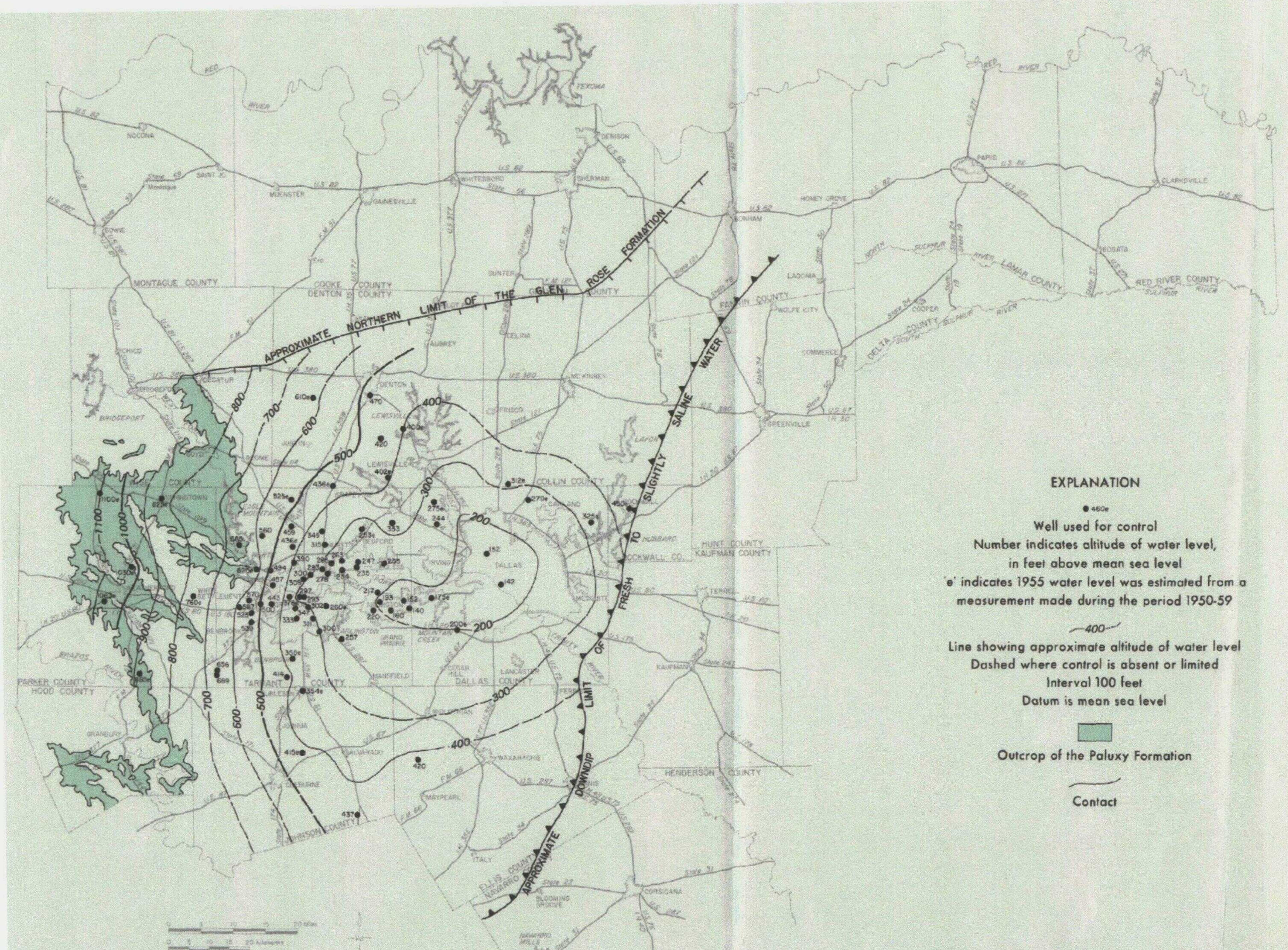
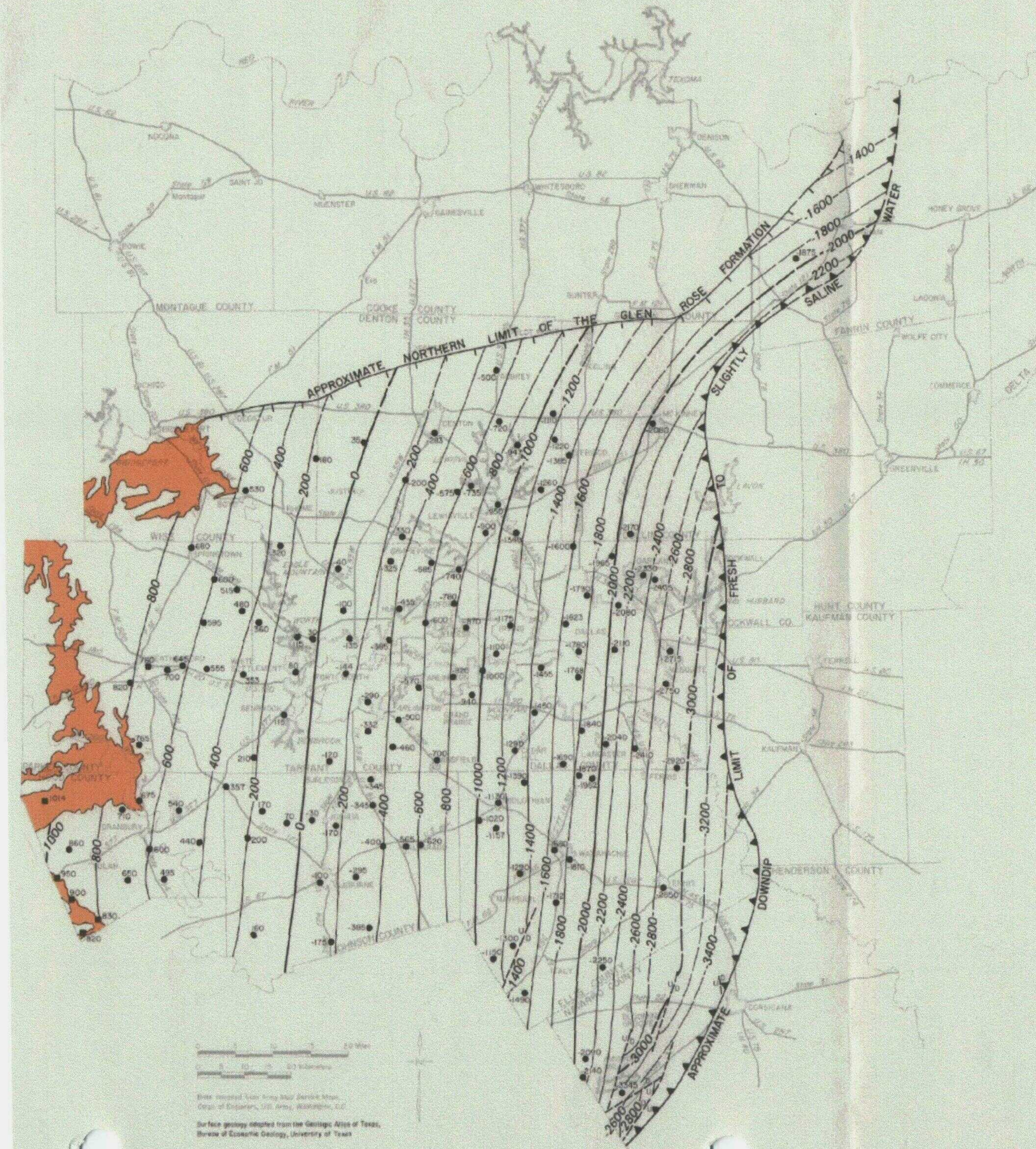


Figure 30
Approximate Altitude of Water Levels in the Paluxy Aquifer, About 1955



EXPLANATION

• 540

Well used for control
Number indicates altitude of top of the Twin Mountains Formation, in feet above or below (-) mean sea level

■ 820

Outcrop control point
Number indicates altitude of top of the Twin Mountains Formation, in feet above mean sea level

—200—

Line showing approximate altitude of top of the Twin Mountains Formation
Dashed where control is absent or limited
Interval 200 feet
Datum is mean sea level

U D

Approximate location of fault
U, upthrown side; D, downthrown side

Outcrop of the Twin Mountains Formation

Contact
Dashed where covered or approximately located

Some data adapted from Klemt and others, 1975 and Thompson, 1972

Figure 19
Approximate Altitude of the Top of the Twin Mountains Formation

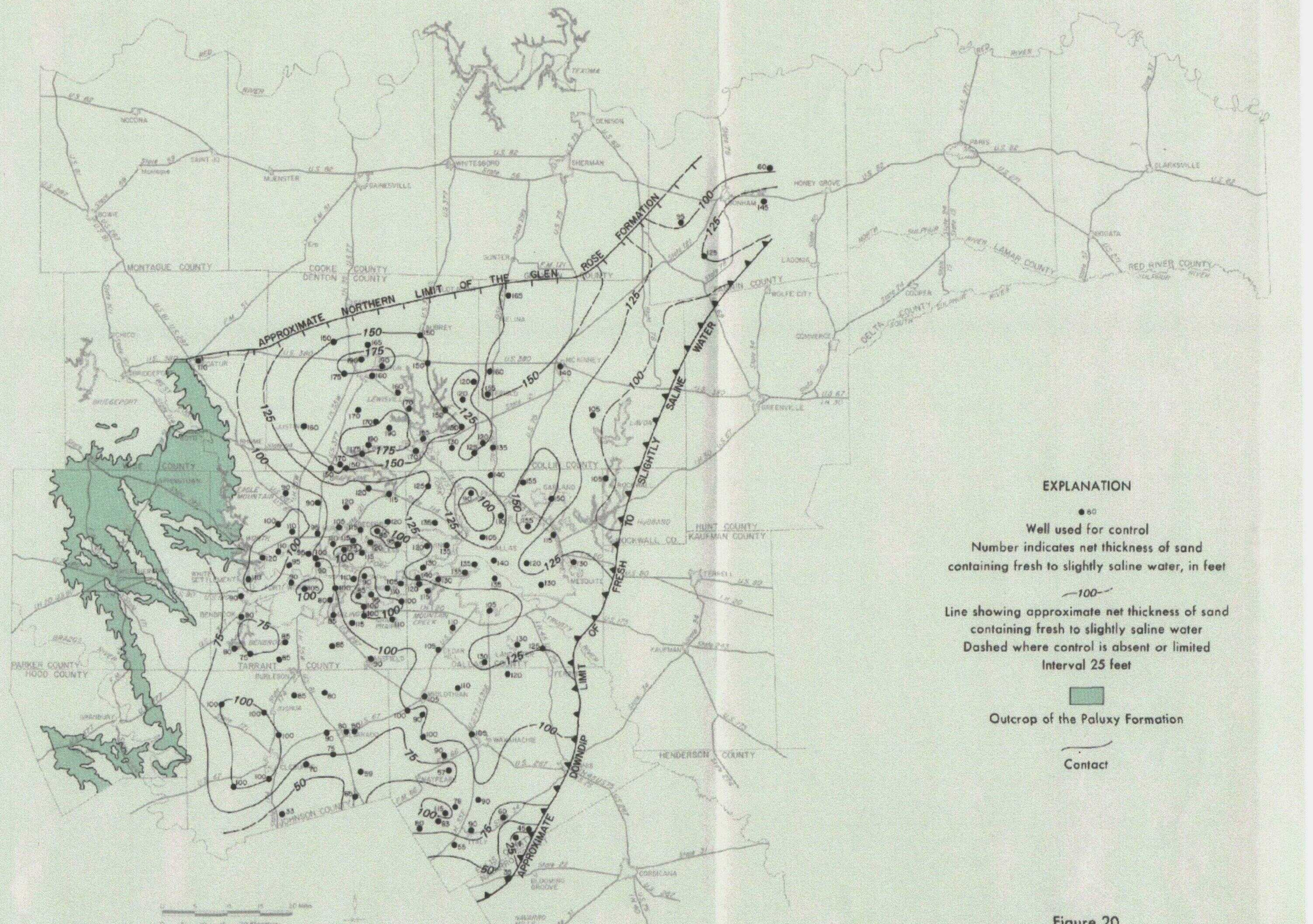


Figure 20

Approximate Net Thickness of Sand Containing Fresh to Slightly Saline Water in the Paluxy Aquifer

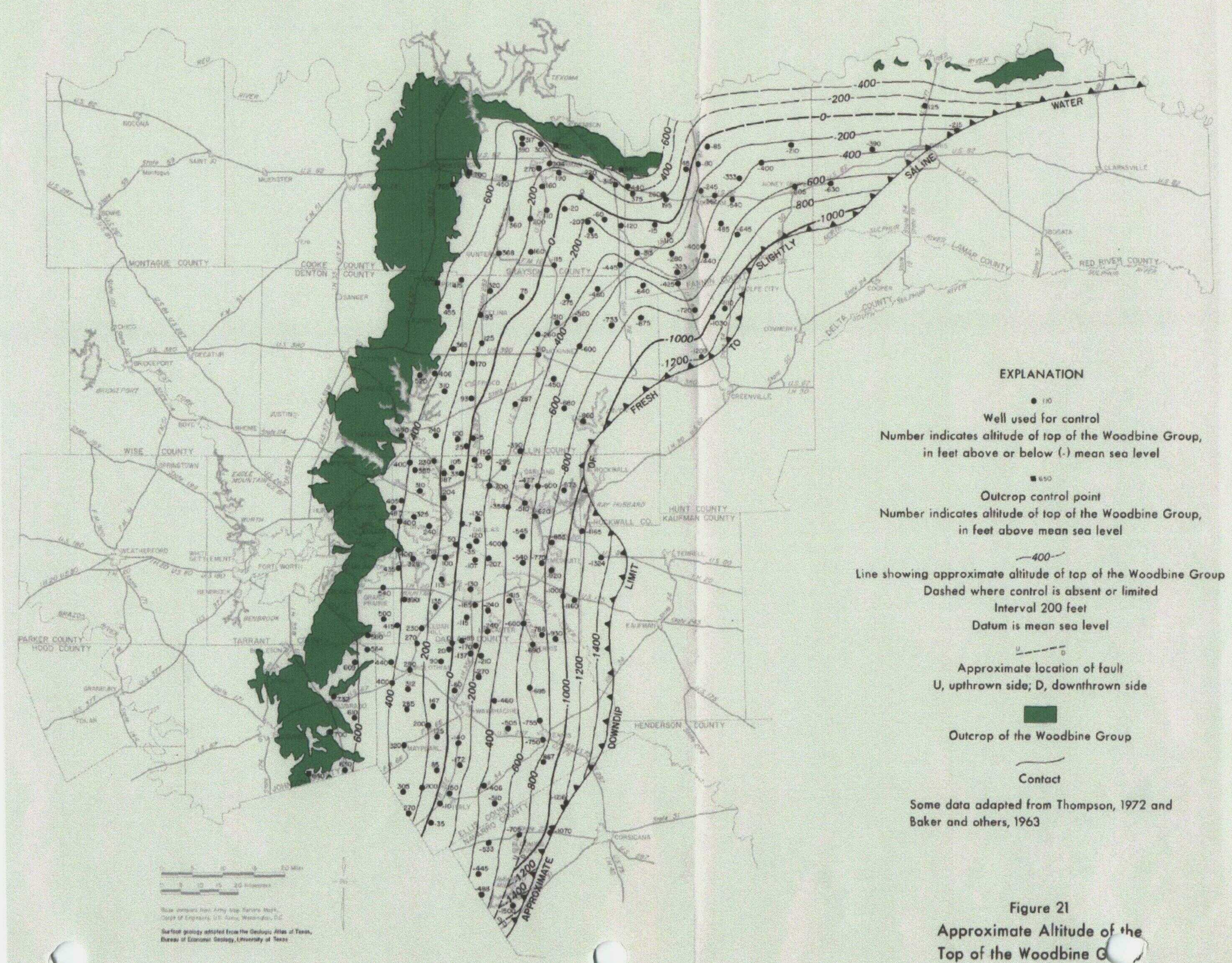
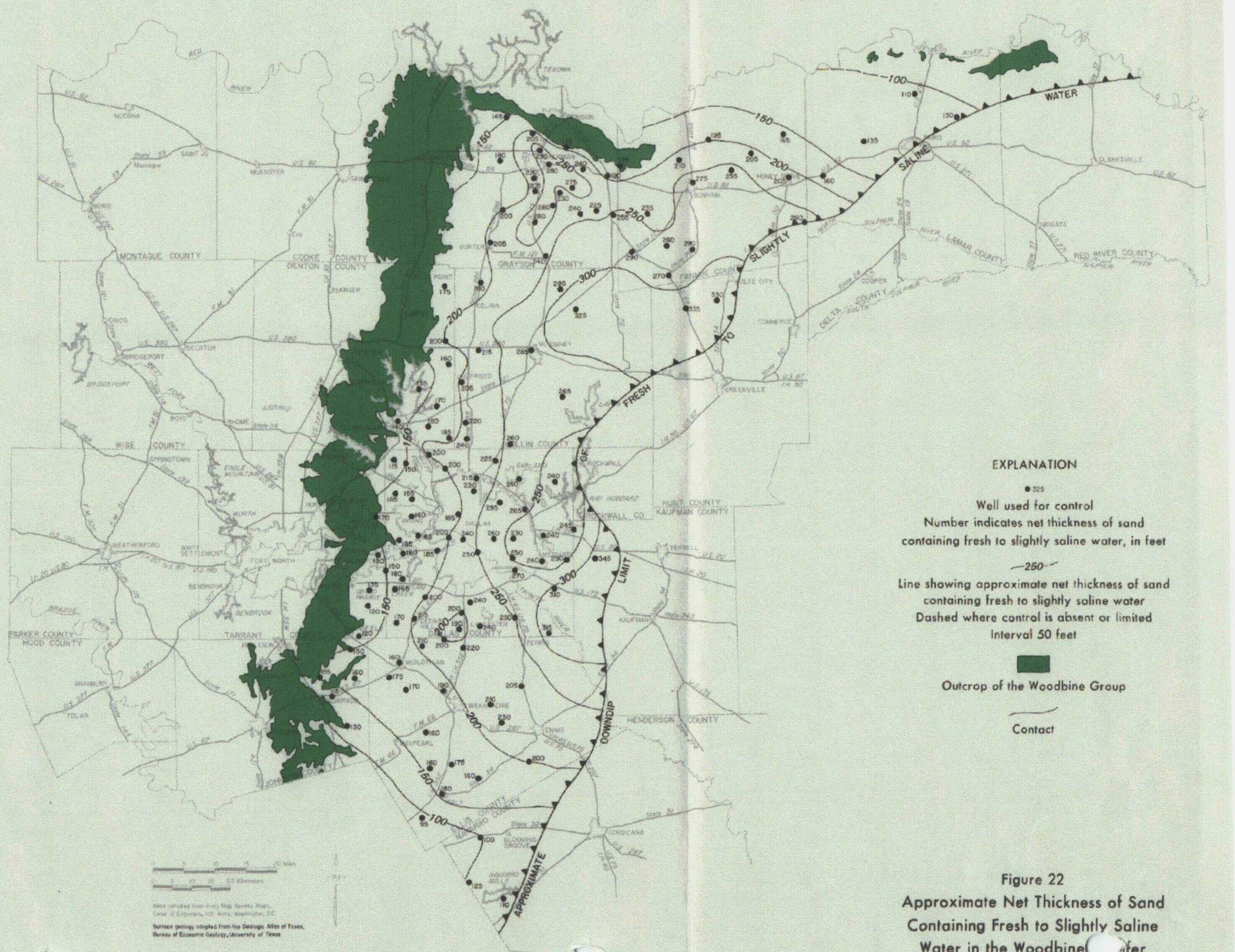


Figure 21

Approximate Altitude of the Top of the Woodbine G[roup]



Surface geology adapted from the Geologic Atlas of Texas, Bureau of Economic Geology, University of Texas

EXPLANATION

• 325

Well used for control
Number indicates net thickness of sand containing fresh to slightly saline water, in feet

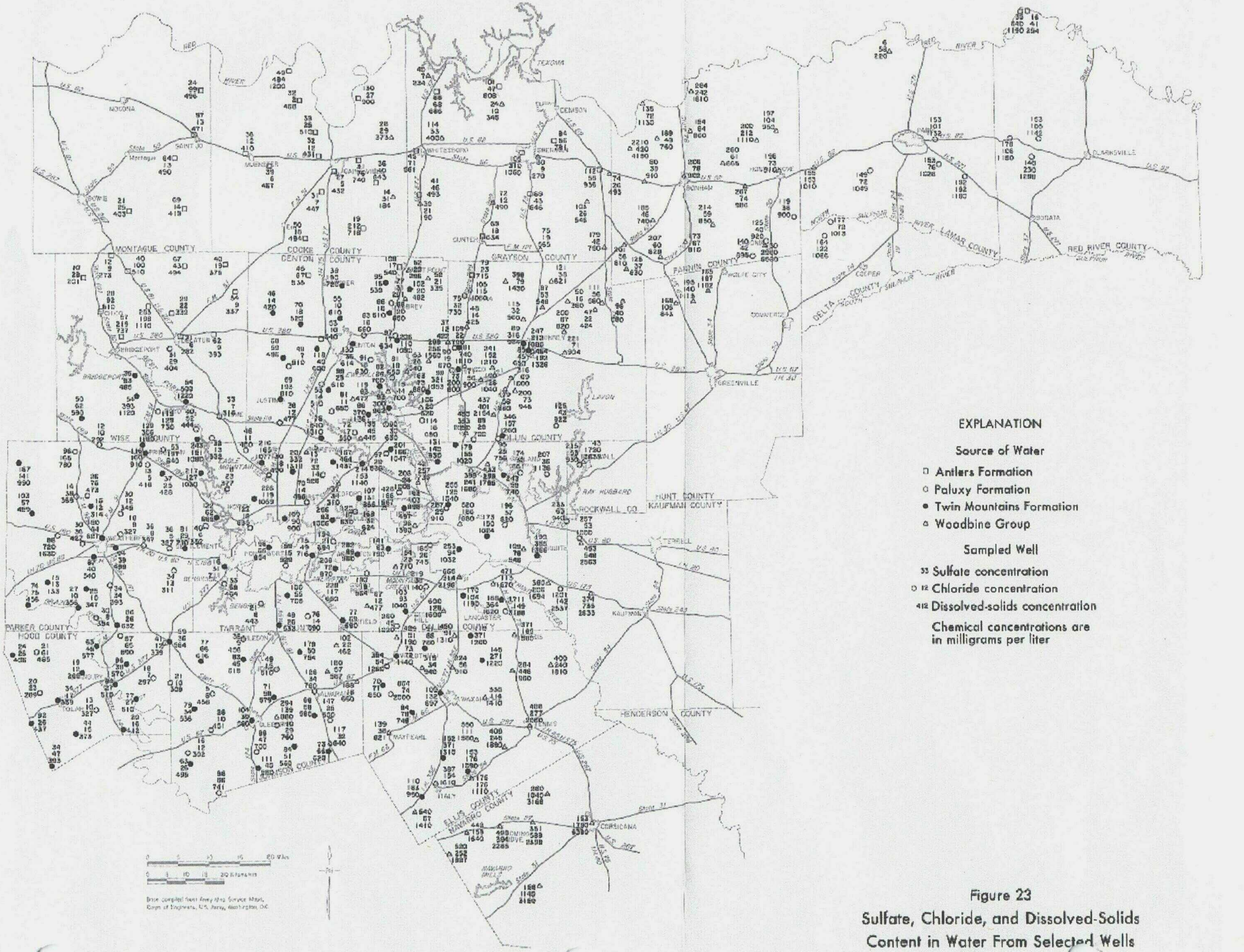
—250—

Line showing approximate net thickness of sand containing fresh to slightly saline water
Dashed where control is absent or limited
Interval 50 feet

Outcrop of the Woodbine Group

Contact

Figure 22
Approximate Net Thickness of Sand Containing Fresh to Slightly Saline Water in the Woodbine Aquifer



EXPLANATION

Source of Water

- □ Antlers Formation
- ○ Paluxy Formation
- ● Twin Mountains Formation
- △ Woodbine Group

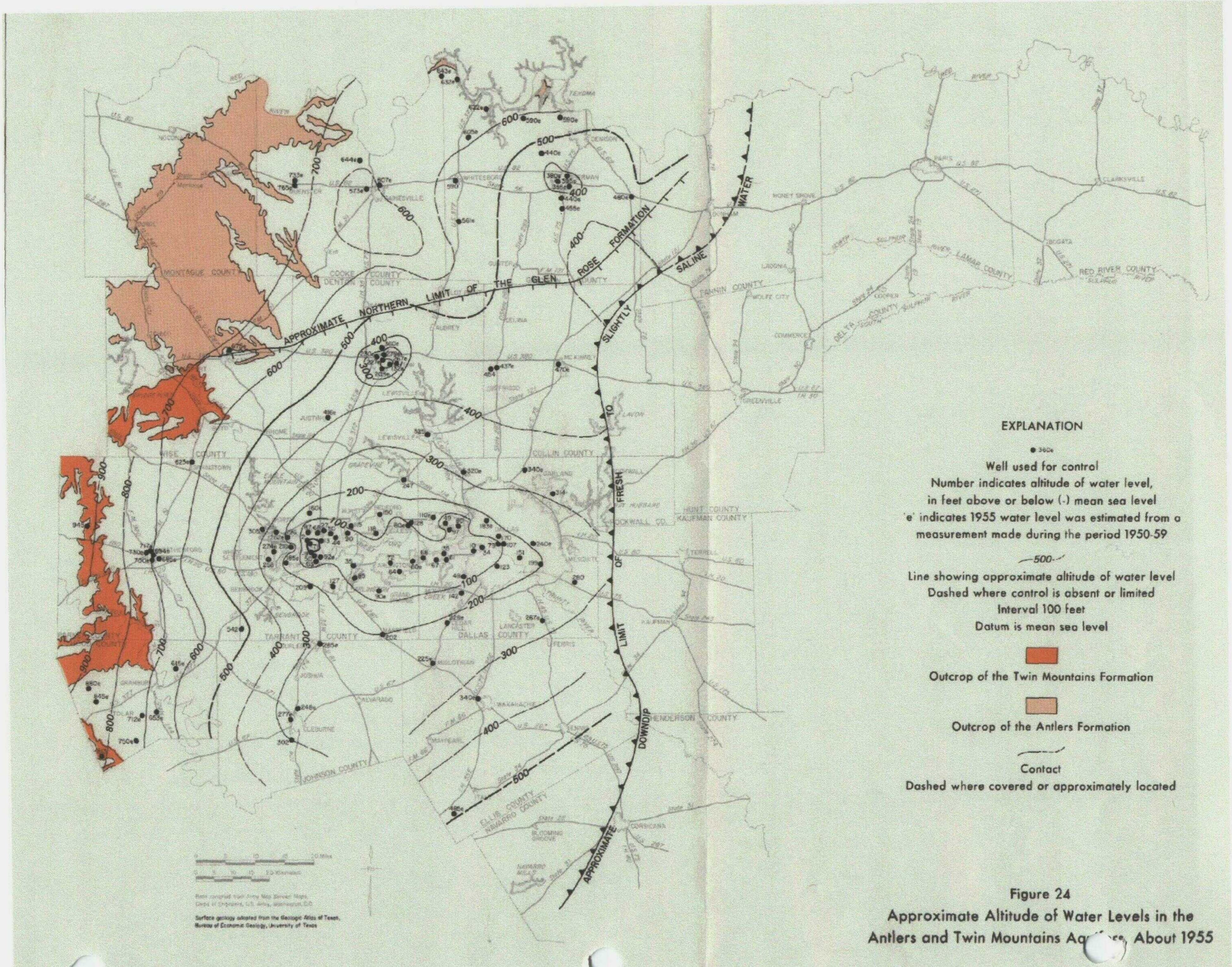
Sampled Well

- 33 Sulfate concentration
- ○ 12 Chloride concentration
- 412 Dissolved-solids concentration

Chemical concentrations are in milligrams per liter

Figure 23

Sulfate, Chloride, and Dissolved-Solids Content in Water From Selected Wells



EXPLANATION

●340e

Well used for control
Number indicates altitude of water level, in feet above or below (-) mean sea level
'e' indicates 1955 water level was estimated from a measurement made during the period 1950-59

—500—

Line showing approximate altitude of water level
Dashed where control is absent or limited
Interval 100 feet
Datum is mean sea level

Outcrop of the Twin Mountains Formation

Outcrop of the Antlers Formation

Contact
Dashed where covered or approximately located

Figure 24
Approximate Altitude of Water Levels in the Antlers and Twin Mountains Aquifers, About 1955

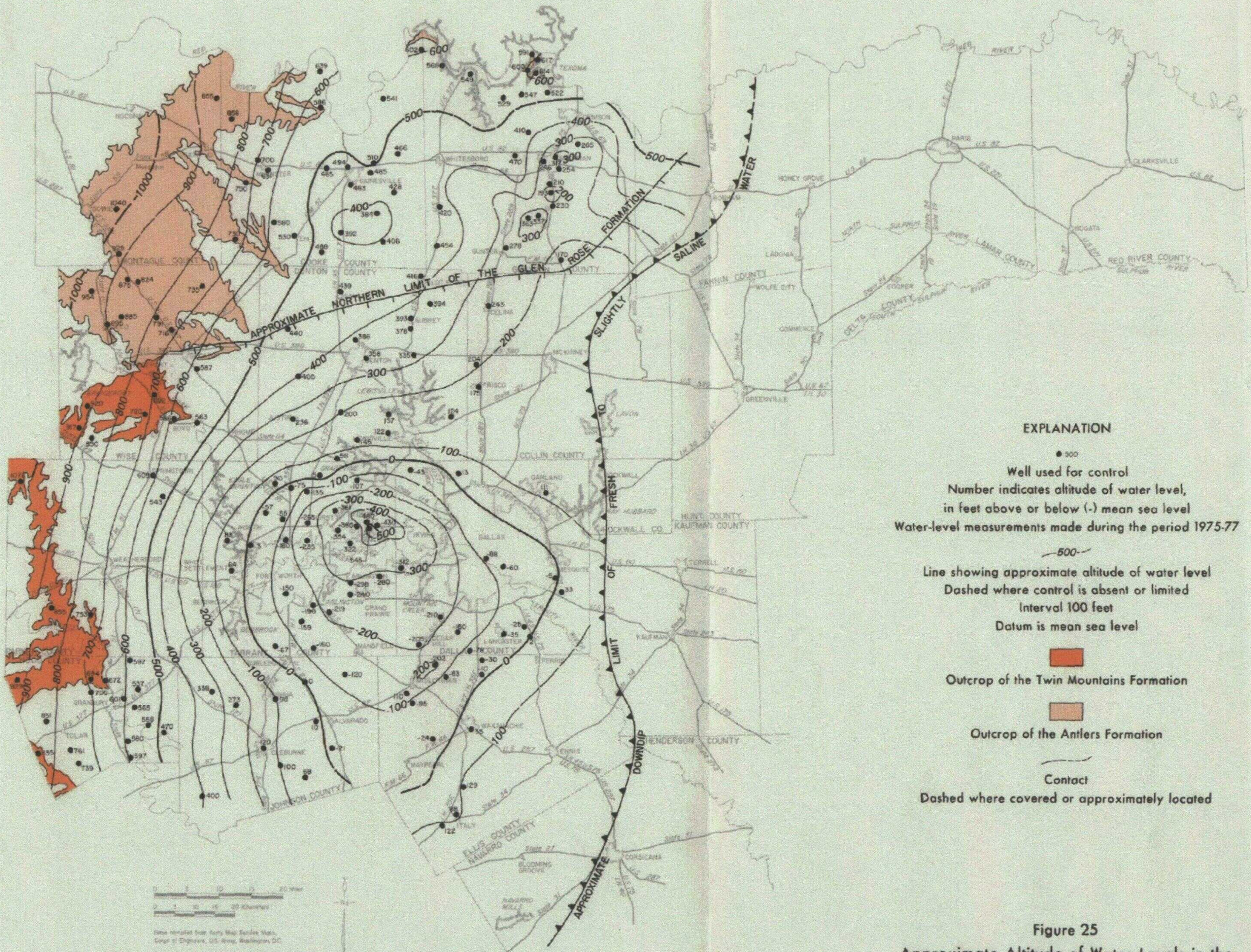


Figure 25

Approximate Altitude of Water Levels in the Antlers and Twin Mountains Aqui[...] About 1976

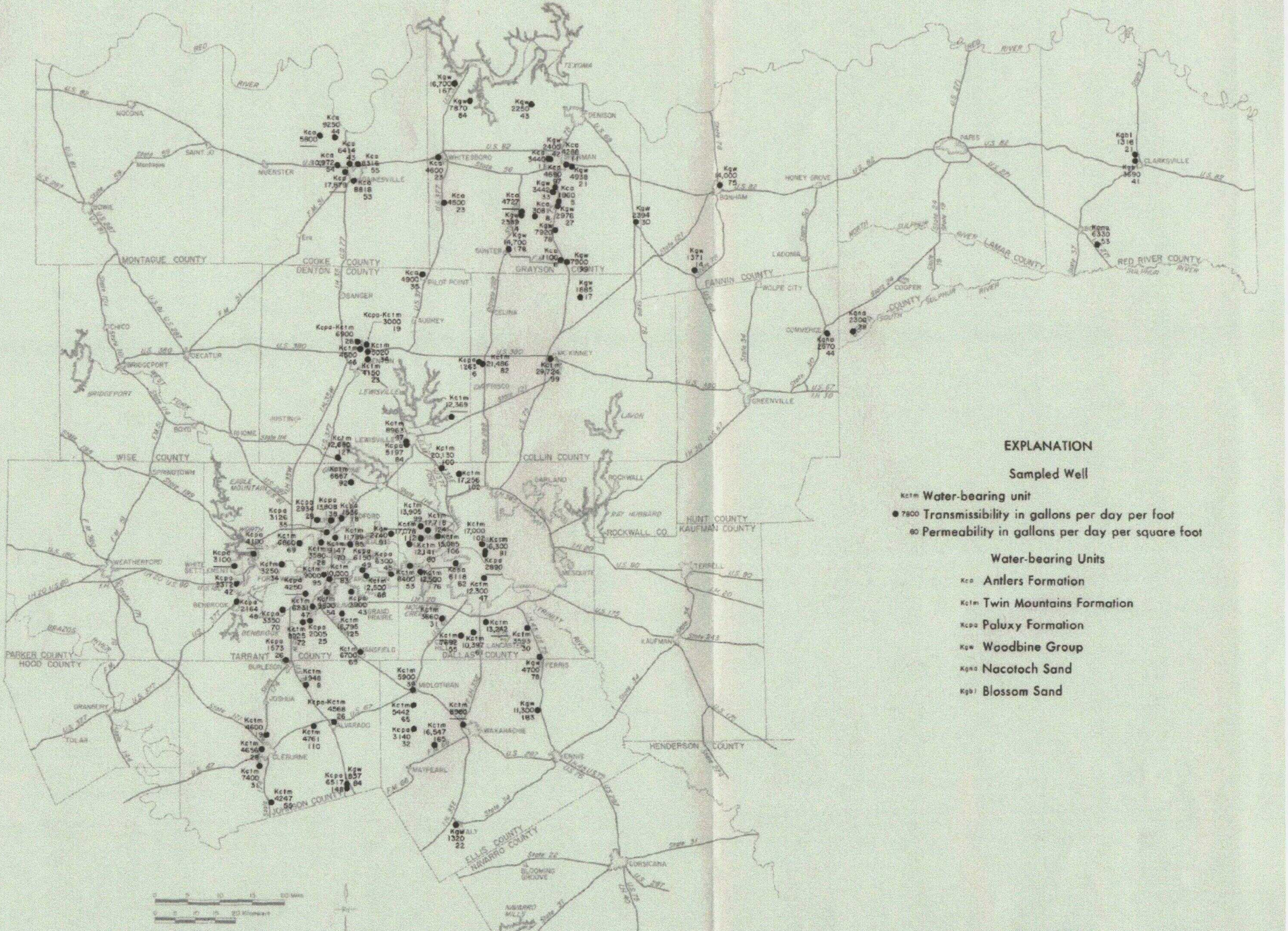


Figure 26

Location of Aquifer Tests and Approximate Coefficients of Transmissibility and Permeability

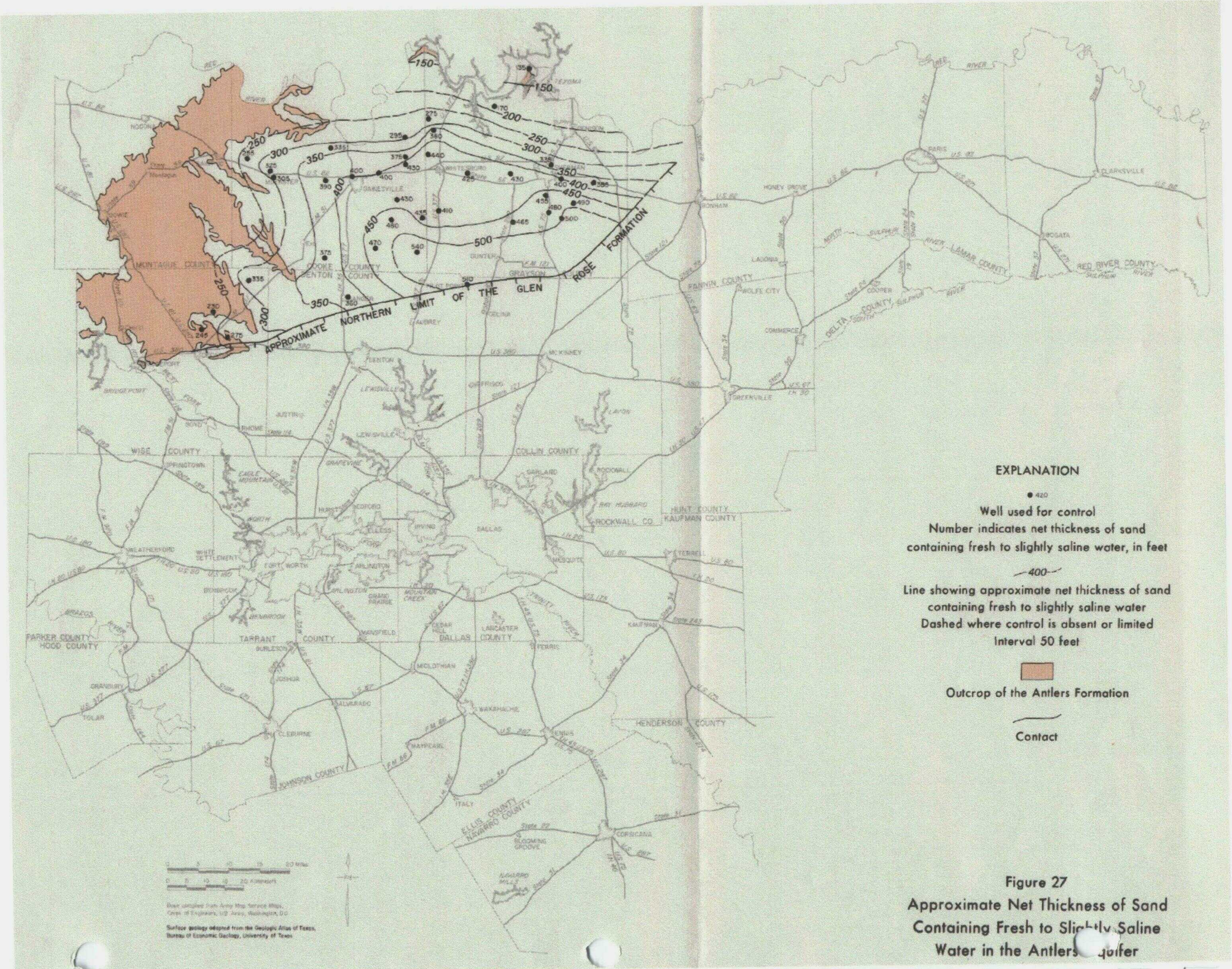


Figure 27

Approximate Net Thickness of Sand Containing Fresh to Slightly Saline Water in the Antlers Aquifer

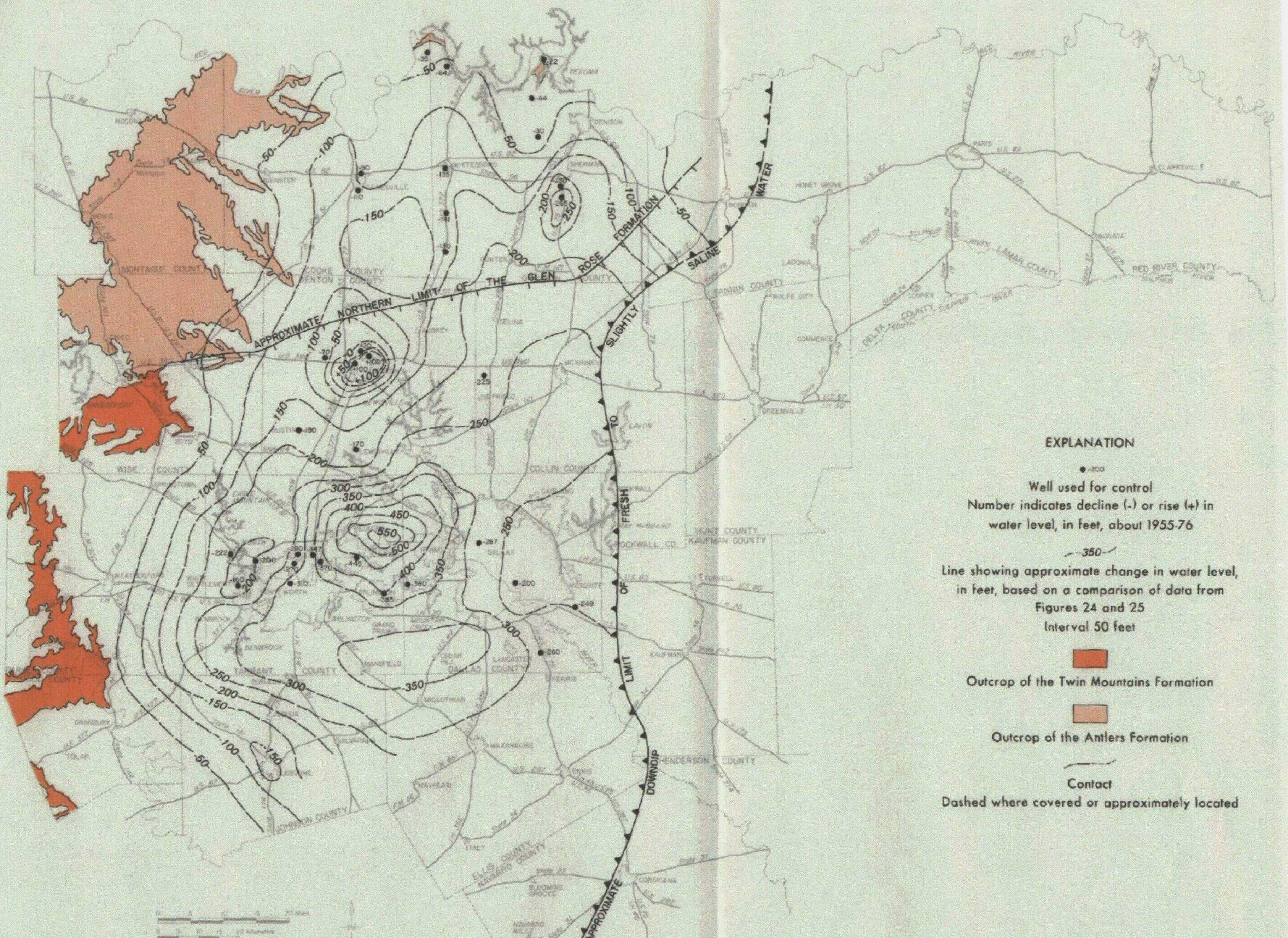
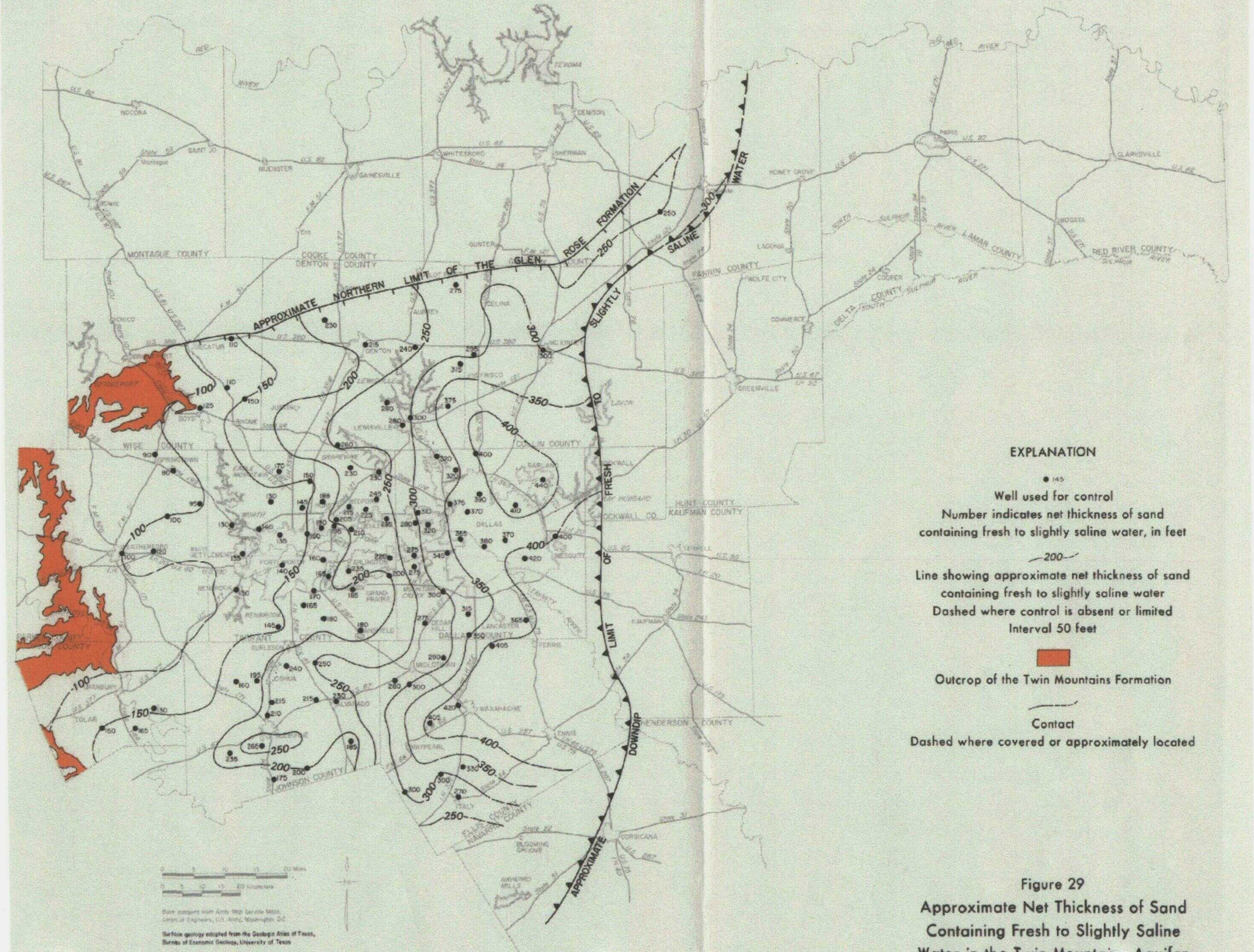


Figure 28
Approximate Change in Water Levels in the Antlers and Twin Mountains Aquifers, About 1955-76



EXPLANATION

• 145

Well used for control

Number indicates net thickness of sand containing fresh to slightly saline water, in feet

—200—

Line showing approximate net thickness of sand containing fresh to slightly saline water

Dashed where control is absent or limited

Interval 50 feet

Outcrop of the Twin Mountains Formation

Contact

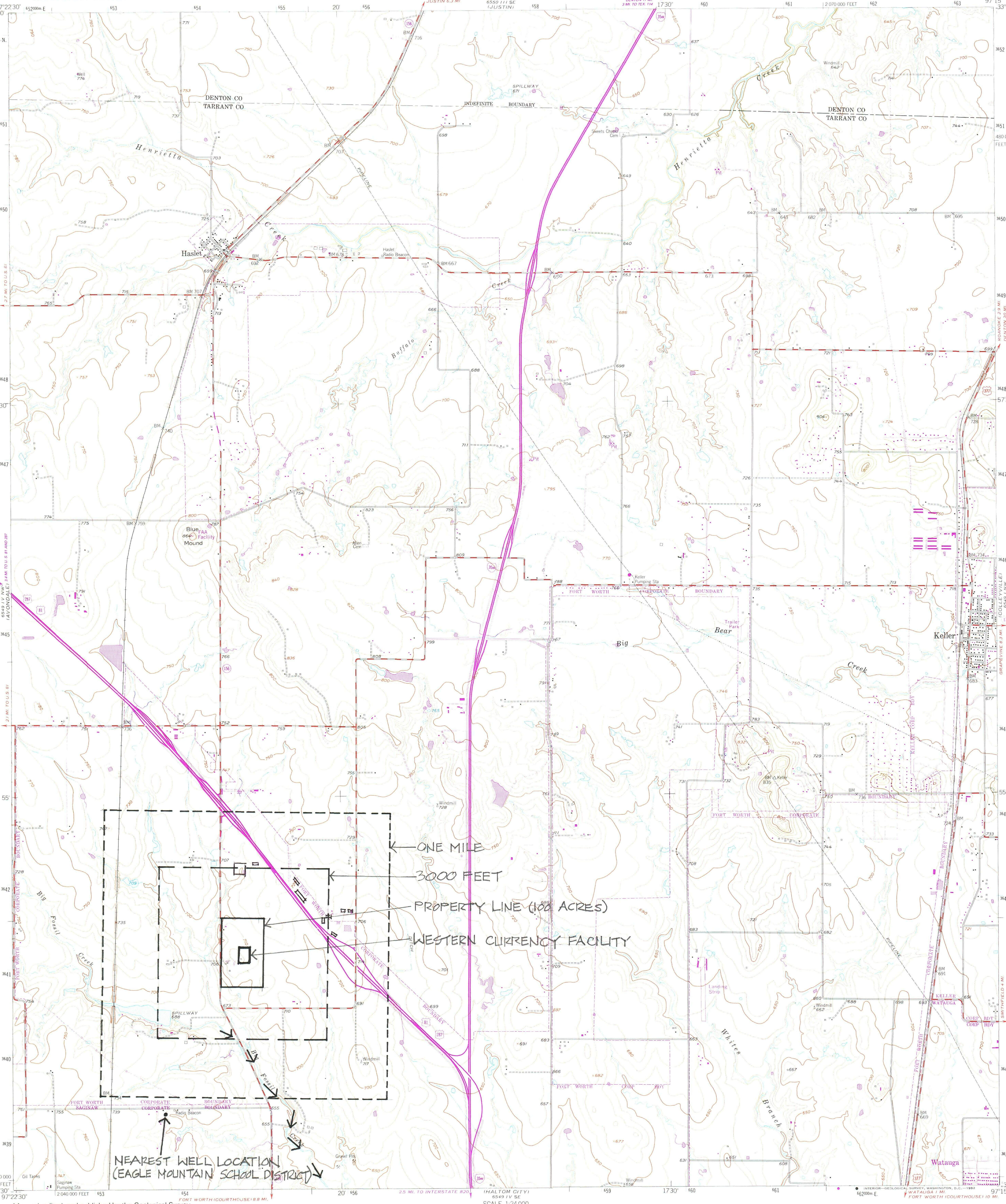
Dashed where covered or approximately located

Figure 29

Approximate Net Thickness of Sand Containing Fresh to Slightly Saline Water in the Twin Mountains Aquifer

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

KELLER QUADRANGLE
TEXAS
7.5 MINUTE SERIES (TOPOGRAPHIC)



Mapped, edited, and published by the Geological Survey

Control by USGS and NOS/NOAA

Topography by photogrammetric methods from aerial photographs taken 1954. Field checked 1955

Polyconic projection. 10,000-foot grid ticks based on Texas coordinate system, north central zone
1000-meter Universal Transverse Mercator grid ticks, zone 14, shown in blue. 1927 North American Datum
The difference between 1927 North American Datum and North American Datum of 1983 (NAD 83) for 7.5 minute intersections is given in USGS Bulletin 1875. The NAD 83 is shown by dashed corner ticks

MN
GN
0°55′
16 MILS
7°
142 MILS

UTM GRID AND 1981 MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET

Revisions shown in purple and woodland compiled from aerial photographs take 1978 and other source data
This information not field checked. Map edited 1981

SCALE 1:24 000

1 ½ 0 1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 .5 0 1 KILOMETER

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR RESTON, VIRGINIA 22092
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

TEXAS
QUADRANGLE LOCATION

3297-434

ROAD CLASSIFICATION

Heavy-duty
Light-duty
Medium-duty
Unimproved dirt
Interstate Route
U. S. Route
State Route

← SURFACE WATER DRAINAGE ROUTE

KELLER, TEX.
32097-H3-TF-024

1955
PHOTOREVISED 1981
DMA 6549 IV NE-SERIES V882